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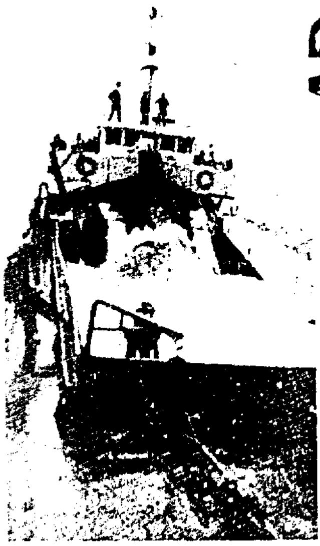

EVALUATION OF CLAMSHELL DREDGING AND BARGE OVERFLOW, MILITARY OCEAN TERMINAL SUNNY POINT, NORTH CAROLINA

by

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The 1987 maintenance dredging for the Military Ocean Terminal, Sunny Point (MOTSU), North Carolina, project was performed by mechanical clamshell dredge, with material placed in barges and transported to an open-water ocean disposal site. This work was the first major use of mechanical clamshell equipment in North Carolina. Resource agencies were concerned with operational procedures for clamshell dredges from the standpoint of potential resuspension of sediment during the dredging process and overflow of barges to increase load. A field study was therefore conducted to give site-specific information on the clamshell operation at MOTSU.

The loading characteristics of the barges for both overflow and nonoverflow conditions and potential gain in load due to overflow were determined for three barge loads. The load gained during the period of overflow varied from 1.4 to 3.2 percent, with

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corresponding times of overflow from 9 to 26 min. The load gained by filling the disposal barge in one test from a level 1 ft (0.3 m) below the coaming to the point of overflow was approximately 6.9 percent. This, added to the load gained during overflow, corresponded to a total increase in load of 10.1 percent for this test.

The suspended solids concentration of the overflow increased with time of overflow. The average concentration at the start of overflow was 88 g/ℓ as compared with 248 g/ℓ at the end of overflow. Measurements of grain size distribution of material retained in the barges and of the overflow indicated that a sorting process occurs in the barges during overflow. This could be due either to settling of sand particles or to an initially finer distribution of the more fluid fractions of the material which comprise the overflow.

Plumes from the clamshell bucket spillage were observed to be patchy in nature, were advected downcurrent, and mixed with the ambient water downstream. The average suspended solids concentration of samples in the plumes generated by dredging was 47 mg/ℓ above the background, while that for plumes generated by dredging with overflow was 65 mg/ℓ above background. The suspended solids concentrations in the plumes were reduced to near-background levels at short distances from the dredging activity. An analytical model indicated the material in the plumes settles rapidly without being transported, and only a small fraction of the suspended material would go into far-field suspension.

A literature review was conducted to evaluate the potential biological effects of the dredging and overflow. Although technical information currently available was found to be insufficient to accurately predict degrees of risk, qualitative predictions are possible. Eggs, larvae, juveniles, and adult forms of estuarine-dependent fish and shellfish species appear to be very tolerant to elevated suspended solids concentrations. When viewed against data on naturally occurring minimum, average, and maximum suspended sediment concentrations (and their temporal and spatial scales) at this site, the suspended sediment levels observed during dredging and overflow most probably did not produce any significant adverse environmental effect.

PREFACE

This report describes a pilot study evaluation of mechanical clamshell dredging and barge overflow operations at the Military Ocean Terminal, Sunny Point, NC. This work was conducted for the US Army Engineer (USAE) District, Wilmington, by the Environmental Laboratory (EL) and the Hydraulics Laboratory (HL) of the US Army Engineer Waterways Experiment Station (WES). Funding was provided by the USAE District, Wilmington, under Intra-Army Order for Reimbursable Services No. CESAW-PD-E-87-103, 21 September 1987. The USAE District, Wilmington, Project Manager for the study was Mr. Philip M. Payonk.

Funds for publication of this report were provided by the Dredging Operations Technical Support (DOTS) Program of the Headquarters, US Army Corps of Engineers (HQUSACE). The DOTS Program is managed under the Environmental Effects of Dredging Programs (EEDP) of the EL. Dr. Robert M. Engler was Manager of the EEDP; Mr. Thomas R. Patin was the DOTS Coordinator. Mr. Joseph Wilson was Technical Monitor for the HQUSACE.

The report was prepared by Dr. Michael R. Palermo, Research Projects Group, Environmental Engineering Division (EED), EL; Mr. Allen M. Teeter, Estuarine Processes Branch (EPB), Estuaries Division (ED), HL; and Dr. Jurij Homziak, formerly of the Coastal Ecology Group (CEG), Environmental Resources Division (ERD), EL. Mr. Larry G. Caviness, EPB, conducted laboratory settling tests described in Part IV. Laboratory analyses described in Parts III and IV were conducted by the USAE Division, South Atlantic, laboratory. Field sampling was conducted by the USAE District, Wilmington. The North Carolina Department of Natural Resources and Community Development assisted in field monitoring and in review of the study plan. Technical review of the report was provided by Mr. Payonk; Mr. Donald Hayes, EED, EL; Dr. Mark LaSalle, ERD, EL; and Ms. Tammy Smith-Dozier and Mr. Walter Pankow, ED, HL. Dr. Palermo served as WES study coordinator. The report was edited by Mr. Jessica S. Ruff of the WES Information Technology Laboratory.

The study was conducted under the direct supervision of Dr. Raymond L. Montgomery, Chief, EED; Mr. Jack Pullen, Chief, CEG; and Mr. George M. Fisackerly, Chief, EPB; and under the general supervision of Dr. Conrad Kirby, Chief, ERD; Mr. William H. McAnally, Jr., Chief, ED; Mr. Frank A. Herrmann, Jr., Chief, HL; and Dr. John Harrison, Chief, EL.

Commander and Director of WES was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
tons (2,000 pounds, mass)	907.1847	kilograms

EVALUATION OF CLAMSHELL DREDGING AND BARGE OVERFLOW, MILITARY OCEAN TERMINAL, SUNNY POINT, NORTH CAROLINA

PART I: INTRODUCTION

Background

1. Maintenance dredging is performed on an annual basis at the Military Ocean Terminal, Sunny Point (MOTSU), North Carolina, by the US Army Engineer District, Wilmington. In past years, dredging was performed by pipeline cutterhead dredges, and the dredged material was pumped to nearby confined disposal areas. However, no suitable confined disposal capacity is now available.

2. The 1987 maintenance dredging for the MOTSU project was performed by mechanical clamshell dredge, with material placed in barges and transported to an ocean disposal site designated by the US Environmental Protection Agency. This work was the first major use of mechanical clamshell equipment in North Carolina. State resource agencies were concerned with operational procedures for clamshell dredges from the standpoint of potential resuspension of sediment during the dredging process and overflow of barges to increase load.

3. A field study was therefore designed to give site-specific information on the clamshell operation at MOTSU. This study was conducted as a cooperative effort between the Wilmington District and the US Army Engineer Waterways Experiment Station. The North Carolina Department of Natural Resources and Community Development assisted in field data collection and review of the study plan. This report describes the results of that field study.

Purpose and Scope

4. The purposes of the field study were to:

a. Determine the loading characteristics of the barges for both overflow and nonoverflow conditions and potential gain in load due to overflow.

b. Determine the characteristics of the barge overflow.

c. Determine the background suspended sediment/turbidity characteristics at MOTSU for the period of concern.

d. Determine the characteristics of the suspended sediment/turbidity plume resulting from the clamshell operation without overflow.

e. Determine the characteristics of the suspended sediment/turbidity plume resulting from the clamshell operation with overflow.

f. Describe the potential effects of observed suspended sediment concentrations on aquatic organisms.

5. The study was designed as a pilot field evaluation conducted during a limited period in which barge overflow was approved by State regulatory agencies. The field study included background monitoring of water quality and hydrodynamic conditions in the MOTSU project area; data collection on dredge operating characteristics; sampling and testing of material in the loaded barges; sampling and testing of material comprising the barge overflow; monitoring of the loading characteristics of the barges; and monitoring of the suspended solids plumes generated both by dredging and dredging with overflow.

6. The field and laboratory data were used to evaluate the efficiency of the dredging operation and loading gains obtained by overflow of the barges. Characteristics of the overflow, resulting plumes, and the degree of suspended sediment release from the MOTSU facility were determined. An evaluation of the potential biological effects due to observed levels of suspended sediment was made based on available literature concerning the tolerances of resident organisms.

Typical Clamshell Dredging and Barge Overflow Operations

Clamshell dredging

7. Clamshell dredges are commonly used for operations in which the dredged material must be transported in barges to distant disposal areas. The material is removed by mechanical excavation with the clamshell bucket. The crane handling the bucket is typically mounted on a barge, which can be positioned using anchors or spuds. The material is placed directly into barges for transport. Twenty to thirty cycles or bucket loads per hour is typical, but production can vary considerably with characteristics of the material and digging depth (Engineer Manual 1110-2-5025) (US Army Corps of Engineers 1983).

8. Resuspension of sediment during clamshell dredging operations is due to impact of the bucket with the bottom, sediment sloughing, and spillage and

leakage of material from the bucket during the hoisting and swinging action. Some bucket loads may be heaped with excavated material, while some bucket loads may be partially filled with excavated material and entrapped water. The characteristics of an operating clamshell dredge normally result in water column concentrations of resuspended sediment of several hundred milligrams per litre close to the dredge. These concentrations are usually reduced by settling to near background levels within several hundred feet of the dredge (Barnard 1978, Hayes 1986).

Barge overflow

9. Dredge barges or scows are normally used to transport material excavated with clamshell dredges. The barges are often equipped for bottom dumping at the disposal site by use of a split-hull design or by bottom doors. Since the material is mechanically excavated from the channel bottom and placed in the scows, there is less entrainment of water during the dredging cycle than with hydraulic dredging. Residual water in the scow at the beginning of the filling cycle and additional water added during filling is displaced as the scow is filled. If filling is continued past the point at which the scow is full, the overflow is discharged over the sides (sometimes called the gunwales or coaming) of the scow. The overflow consists of a mixture of residual water, entrained water, and solids. If coarse-grained material is dredged, the solids can be "stacked" in the scow above the level of overflow (Palermo and Randall, in preparation).

10. Relatively little technical information is available on the sediment resuspension due to barge overflow. Although several investigations have been conducted to document sediment resuspension due to clamshell operations, it is difficult to isolate the resuspension due to overflow and that due to the excavating action of the bucket (Palermo and Randall, in preparation).

11. Tavolaro (1984) characterized scow overflow as a part of a comprehensive sediment budget study for clamshell dredging and disposal activities. The volume and solids concentration of the overflow was measured for scows of varying size. A large variability in volume, water column solids concentration, and time of overflow was observed. Factors influencing the character of the overflow were intensity of dredging, degree of water entrainment during excavation, length of time of overflow, and the care with which material is placed in the scow. The water column suspended solids due to overflow was found to be approximately equal to that resulting from the clamshell dredging

operation. Tavolaro (1984) drew no conclusions relating to the load gain achieved in the scows by overflowing.

Project Description

12. The MOTSU facility is located on the west bank of the Cape Fear River, approximately 10 miles* upstream from the river's mouth at the Atlantic Ocean and 18 miles downstream from Wilmington (see Figure 1). The estuary is approximately 3,000 ft wide at this point. Depths are generally less than 10 ft at mean low water (mlw) except for the Wilmington Harbor Navigation Channel, which is maintained to a depth of 38 ft below mlw, and the MOTSU navigation channels, which are maintained to a depth of 34 ft below mlw. The mean tidal range at MOTSU is approximately 4 ft. Maximum tidal current velocities for the Wilmington Harbor channel adjacent to MOTSU are approximately 2.2 fps during flood tide and about 2.7 fps during ebb tide. The average daily freshwater inflow to the Cape Fear River estuary over the past 30 years was approximately 9,780 cfs. The Cape Fear estuary is partially to well mixed depending on the river discharge (Payonk, Palermo, and Teeter 1988).

13. The MOTSU harbor facilities include three wharves and three interconnected basins, which are connected by entrance channels to the Wilmington Harbor Federal Navigation Project. A plan of the MOTSU facilities is shown in Figure 2. Dredging is performed annually to maintain the project depth.

14. The maintenance sediments dredged from the MOTSU project are classified as a fat clay (CH, based on the Unified Soil Classification System (USCS)) with traces of sand. Detailed discussion of the in situ sediment characteristics is found in Part III. Chemical and bioassay analyses of the sediments from MOTSU have indicated no elevated concentrations of contaminants (Jones, Edmunds and Associates, Inc. 1979).

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

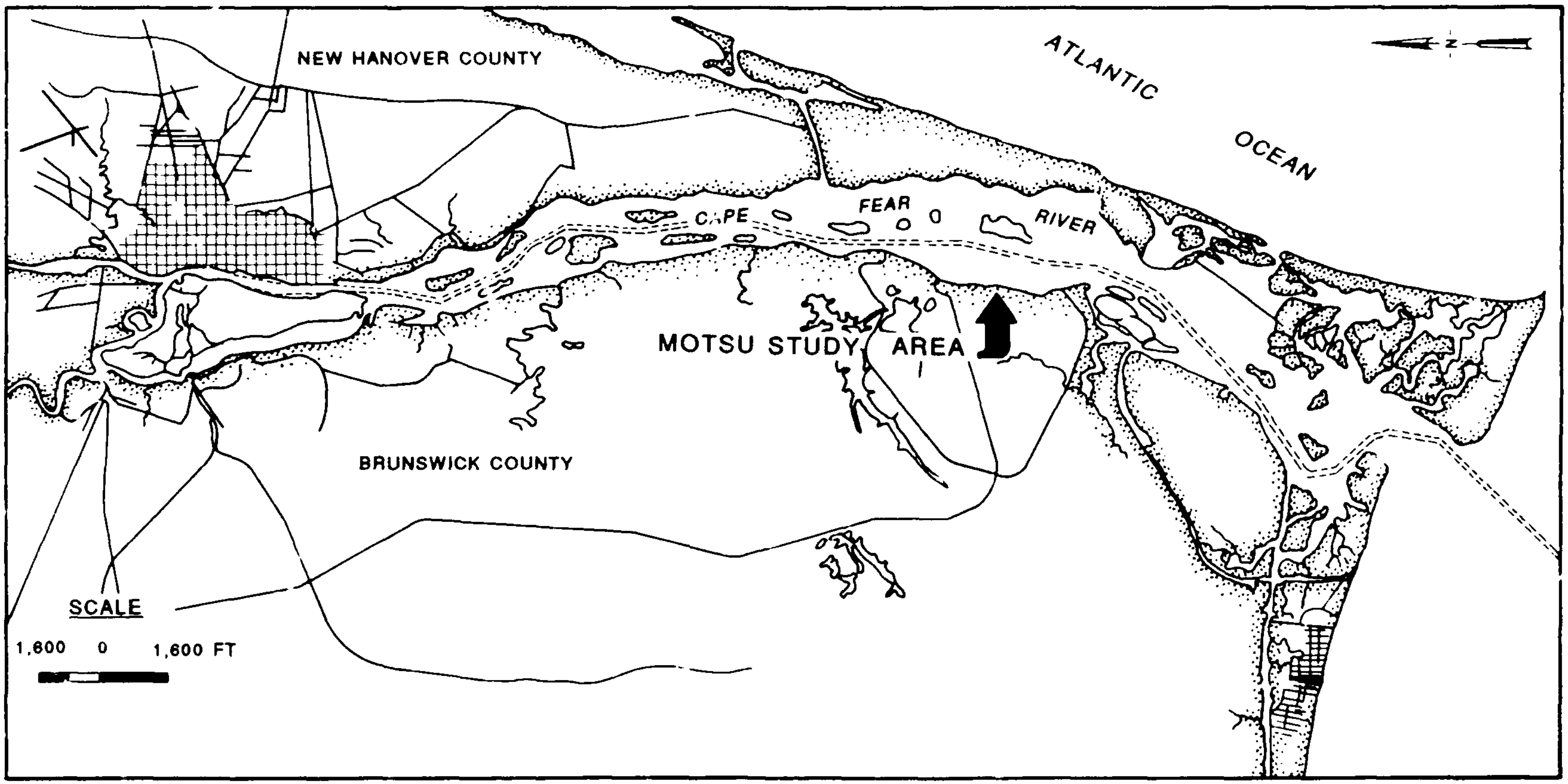


Figure 1. The Cape Fear River estuary, showing the Military Ocean Terminal, Sunny Point

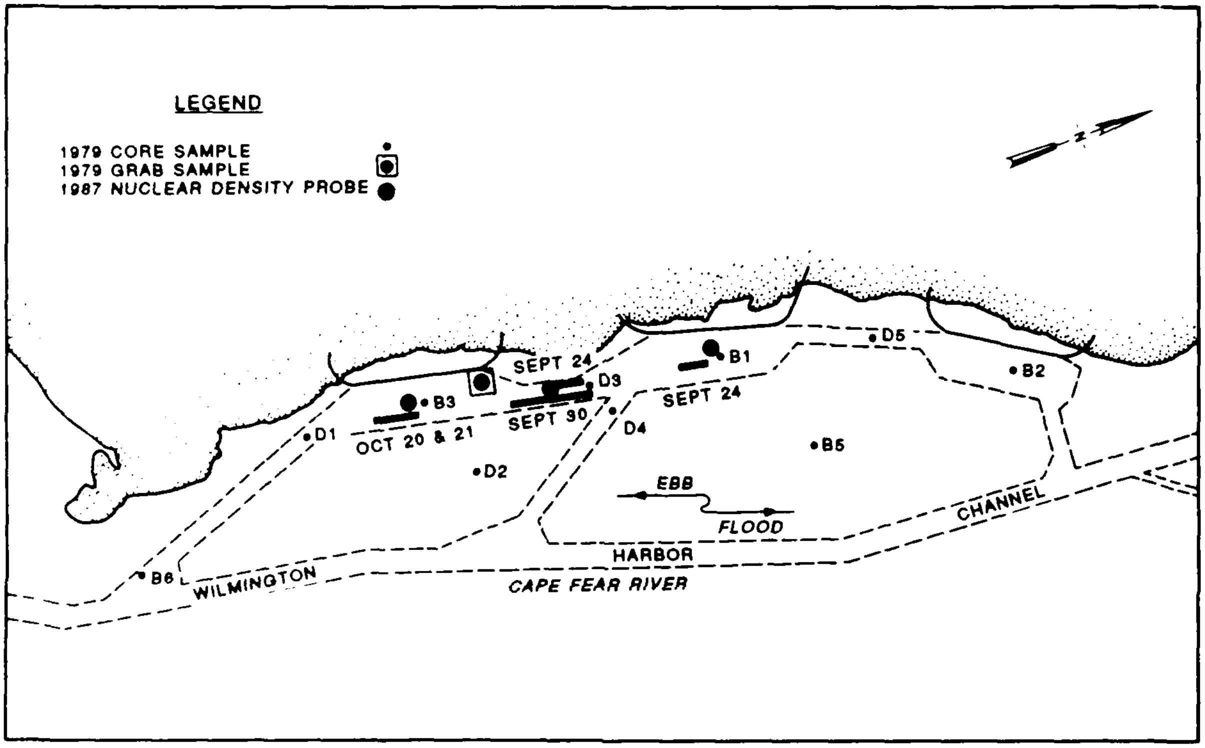


Figure 2. Study area, showing plume sampling stations and areas dredged on specific days

PART II: DREDGING OPERATIONS AND BARGE LOADING CHARACTERISTICS

Dredging Equipment and Operations

15. The field study was conducted during maintenance dredging operations during the period August 12 to December 16, 1987. Approximately 1.5 million cubic yards of material was removed using an 18-cu yd clamshell dredge. Two 4,000-cu yd split-hull scows were used to transport the dredged material to the Wilmington Harbor ocean disposal site, which is located approximately 3.5 miles from the mouth of the Cape Fear River. The barge hopper dimensions were 41 by 168 ft.

16. All dredging was performed without overflow, except for three barge loads during the field study period. Field monitoring of dredging operations without overflow was conducted for 2 days (September 24 and 30). Field monitoring of dredging operations with overflow was conducted during a second 2-day period (October 20-21). The test period in which overflow was allowed was limited to 2 days due to concerns of the State agencies. Three barges were filled past overflow during this period, hereinafter referred to as Tests A, B, and C. No modification to the dredging contract was made for the study. The dredge operator was merely told to overflow the barge until he reached an economic load, using techniques normally employed when overflow was permitted. The locations of the areas dredged and the dates of dredging for the field study are indicated in Figure 2. A photograph of the operating dredge and clamshell bucket is shown as Figure 3.

Barge Loading Characteristics

Measurement techniques

17. The change in total weight of the barge load for Tests A, B, and C was determined from recorded observations of the barge draft. Staff gages were attached to the barges to aid in determining draft. A relationship of load versus draft, shown in Figure 4, was furnished by the dredging contractor. This relationship was used to determine the weight of the load in tons corresponding to observed draft. Drafts were observed and recorded immediately prior to overflow and following completion of overflow. An

Figure 3. Operating dredge and clamshell bucket

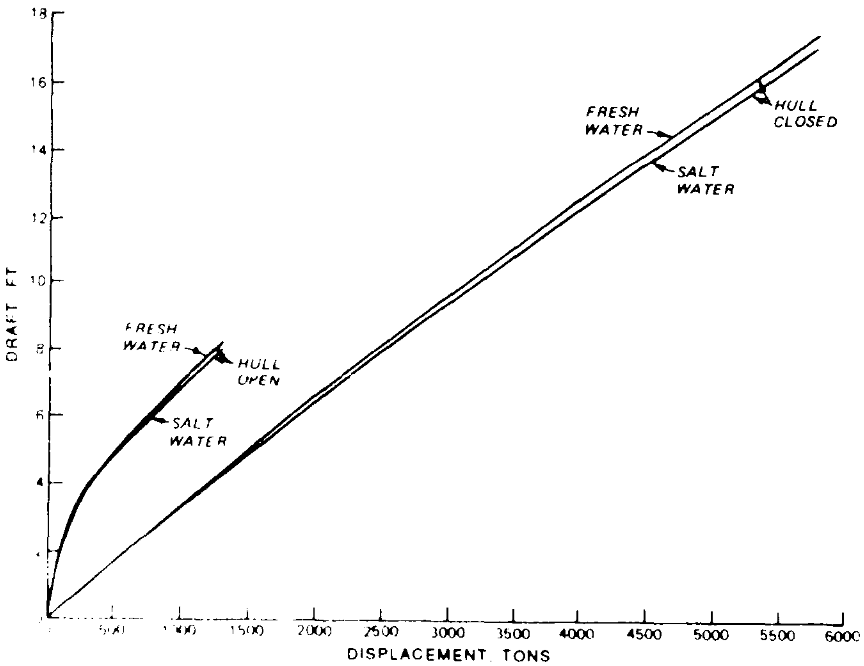


Figure 4. Barge load versus draft relationship

estimate of the volume of material displaced during overflow was made by recording the number of bucket loads placed in the barge during the period of overflow.

18. A nuclear density probe (Troxler 3565 Sediment Density Gage) was used to obtain density profiles in the barges for Tests A and B. Both preoverflow and postoverflow profiles were obtained. No profiles were obtained for Test C because a licensed operator was not available for the day of that test. The profiles were obtained by stationing the probe at the midpoint of the barge hopper opening. In this way, the probe could achieve the deepest possible penetration. Readings were taken from depths ranging from 3 to 20 ft in the loaded barges.

Results based on draft measurements

19. The barge drafts, corresponding barge loads, and percent changes in load following overflow are summarized in Table 1. The start of overflow was considered as the point at which material first began to spill over the barge coaming. The barge draft at the point of filling to approximately 1 ft below the coaming was recorded for Test C. This draft has significance since filling to 1 ft below the coaming would be the point at which the barges would be declared full in cases where no overflow was allowed. The overflow period was ended when the barge operator perceived an economic load and not by measurements indicating a maximum load, i.e., no additional load being gained.

20. The additional load gained during the period of overflow was 75, 125, and 175 tons for Tests A, B, and C, respectively. These gains represent 1.4, 2.4, and 3.2 percent, respectively. For Test C only, the gain in load from a point of filling 1 ft below the coaming was measured. This load gain was a total of 10.1 percent, consisting of a gain of 6.9 percent in filling to the point of overflow and an additional 3.2 percent gained by overflow.

21. A difference in load gain for similar overflow periods was observed for Tests A and B. For Test A, the barge load was increased 75 tons (1.4 percent of load prior to overflow). For this test, the overflow period was 10 min, involving 12 bucket loads. For Test B, the barge load was increased 125 tons (2.4 percent) after an overflow period of 9 min, involving seven bucket loads. These differences in load gain for similar overflow periods are likely due to a combination of factors. First, the estimates of barge load by draft determination are not precise. Second, the material dredged was apparently different from test to test and even from bucket load to bucket load.

Table 1

Barge Drafts and Loads

Test	Observation	Time of Event (Local Time)	Barge Draft ft (m)	Barge Load tons (metric tons)	Percent Change
		October 20, 1987			
A	Start of overflow	1127	15.7 (4.79)	5,325 (4,830)	--
	End of overflow [12]*	1137	15.9 (4.85)	5,400 (4,898)	1.4
B	Start of overflow	1526	15.4 (4.69)	5,200 (4,717)	--
	End of overflow [7]	1535	15.7 (4.79)	5,325 (4,830)	2.4
		October 21, 1987			
C	0.3 m below coaming	1352	15.0 (4.57)	5,050 (4,581)	--
	Start of overflow	1405	15.9 (4.85)	5,400 (4,898)	6.9
	End of overflow [21]	1420	16.4 (5.00)	5,575 (5,057)	3.2

* The number in brackets is the number of bucket loads placed in the barge during the overflow period.

The load at start of overflow for Test B was lower than for Test A (5,200 tons as compared with 5,325 tons). The lower load at start of overflow for Test B means that more material of lower density occupied the barge, and the potential for load gain by overflow was therefore greater. The difference in density in respective bucket loads and the intensity of dredging can obviously account for large differences in load increase with time. It is apparent that the seven bucket loads accounting for a 125-ton load gain in Test B must be of higher density than the 12 bucket loads accounting for a 75-ton load gain in Test A.

22. The load at start of overflow for Test C was higher than for Test A (5,400 tons as compared with 5,325 tons). Comparison of results for Test A and C indicated that load continues to increase with time of overflow for the range of overflow times observed and for barges with similar loads at the start of overflow. As the density of the load in the barge approaches that of the most dense portions of the bucket loads of material being placed in the

barge, no gain in barge load will be realized. Unfortunately, the time of overflow at which this occurred was not determined for any of the tests, because the dredge operator discontinued overflow at the point that he perceived economic load.

Results based on nuclear probe

23. The density profiles from the nuclear probe are shown plotted in Figures 5 and 6. Percentage differences between preoverflow and postoverflow profiles are plotted in Figure 7. Differences in load increases for Tests A and B as indicated by comparisons of nuclear density data were less than those based on draft measurements. The average percentages of change of density were 2.5 and 2.6 for Tests A and B, respectively. However, the trends were the same as discussed above in that a lower increase in load was apparent in Test A even though the overflow period involved a greater dredging effort. It should be noted that the nuclear density data account only for densities at the measured points and were not used to calculate total load in the barges.

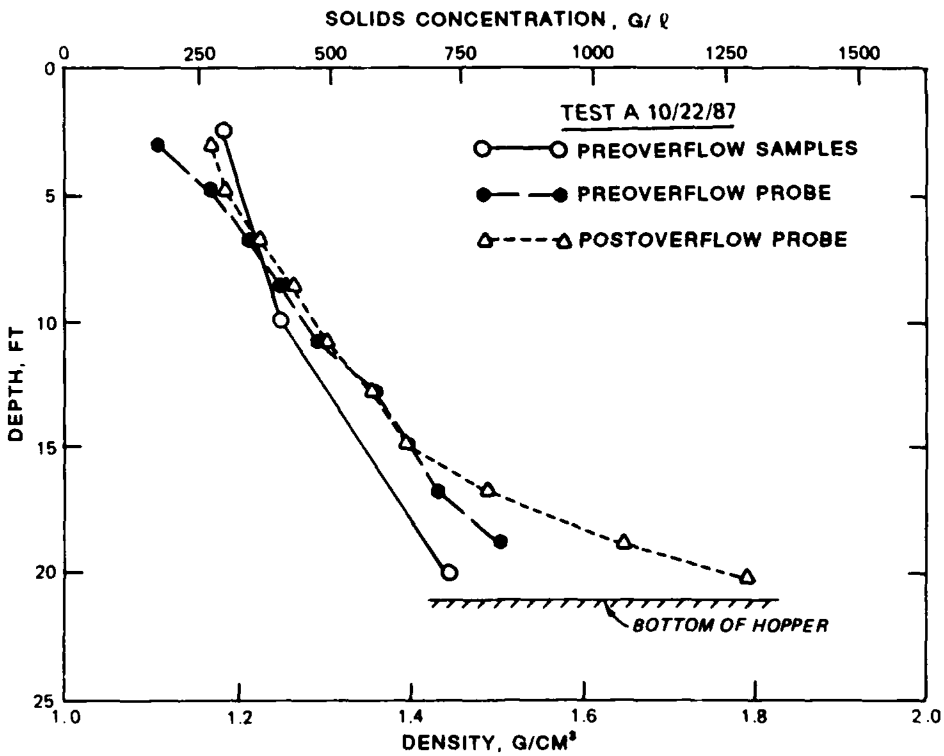


Figure 5. Density profiles for Test A

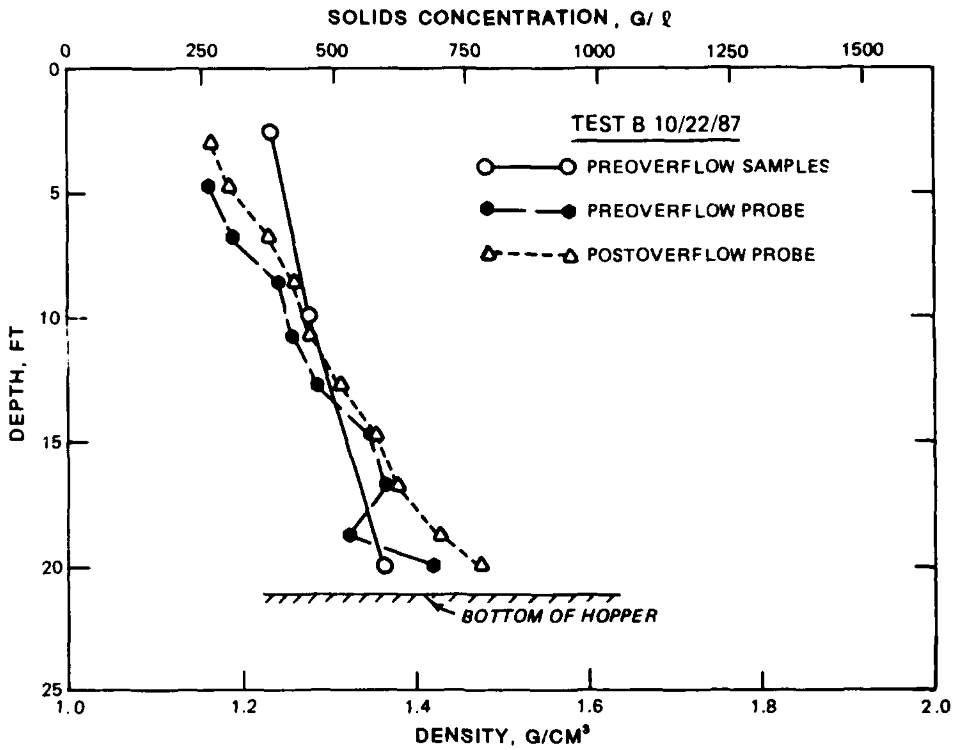


Figure 6. Density profiles for Test B

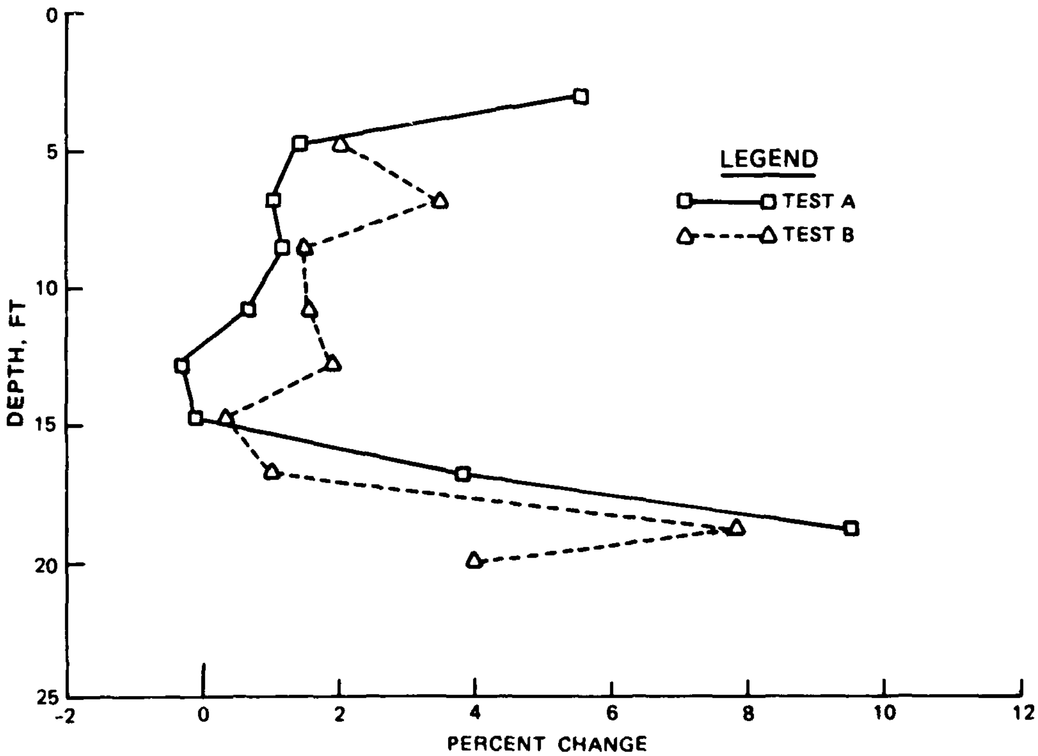


Figure 7. Percent change in density for Tests A and B

PART III: DREDGED MATERIAL AND OVERFLOW CHARACTERISTICS

Characteristics of in situ Sediments

Sampling and testing

24. Shallow core samples were taken throughout the MOTSU channel areas in 1979 (Jones, Edmunds and Associates, Inc. 1979). Three of these cores were taken in the areas dredged during this study. A sediment grab sample was also taken at the south wharf as a part of this study. Locations of the samples are shown in Figure 2. Samples from the cores were analyzed for bulk density and grain size. The grab sample was analyzed for water content, Atterberg limits, and grain size.

25. As a part of this study, the nuclear density probe was used to determine a density profile in the in situ sediment at a location off the south wharf, as shown in Figure 2. The probe was positioned over the edge of the wharf, and the profile was obtained for sediments between a water depth of 24 and 36 ft.

Solids concentration

26. The solids/concentration data from the 1979 core samples and the grab sample for this study were very similar. The bulk density of the 1979 core samples was approximately 1.17 kg/ℓ, which corresponds to a solids concentration of approximately 275 g/ℓ. Water content of the grab sample was 299 percent, which corresponds to a sediment concentration of approximately 325 g/ℓ.

27. The density profile as determined by nuclear density probe is shown in Figure 8. The observed in situ densities (relative to water) vary from 1.01 at the sediment surface (essentially a fluff) to over 1.2 at sediment depths near the 35-ft depth. The equivalent solids concentrations vary from below measurable concentrations to over 450 g/ℓ. The average relative density is 1.15, which corresponds to a solids concentration of approximately 250 g/ℓ.

Grain size distribution

28. Grain size data from the 1979 core samples and the grab samples for this study were very similar. These data indicate that the in situ material is approximately 86 percent silt and clay (finer that 0.074 mm) and 14 percent sand (all on a dry weight basis). The average grain size (D50) is 0.04 mm. The range of grain size distributions of the in situ samples is shown in Figure 9a. It should be noted that the cores and grab samples of in situ channel

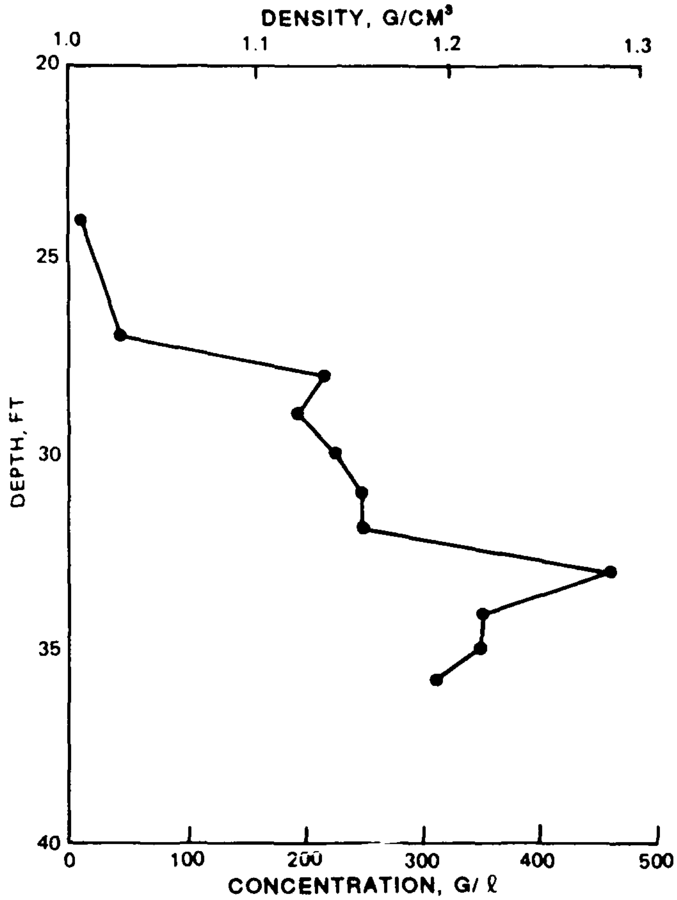
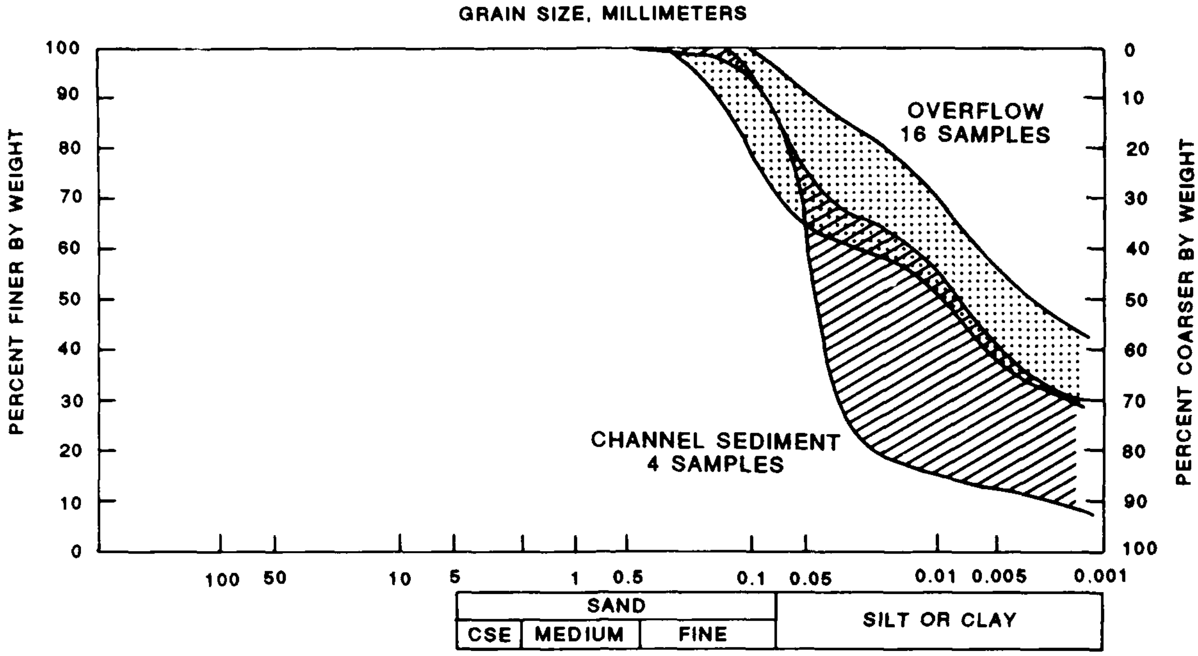


Figure 8. In situ density profile at south wharf

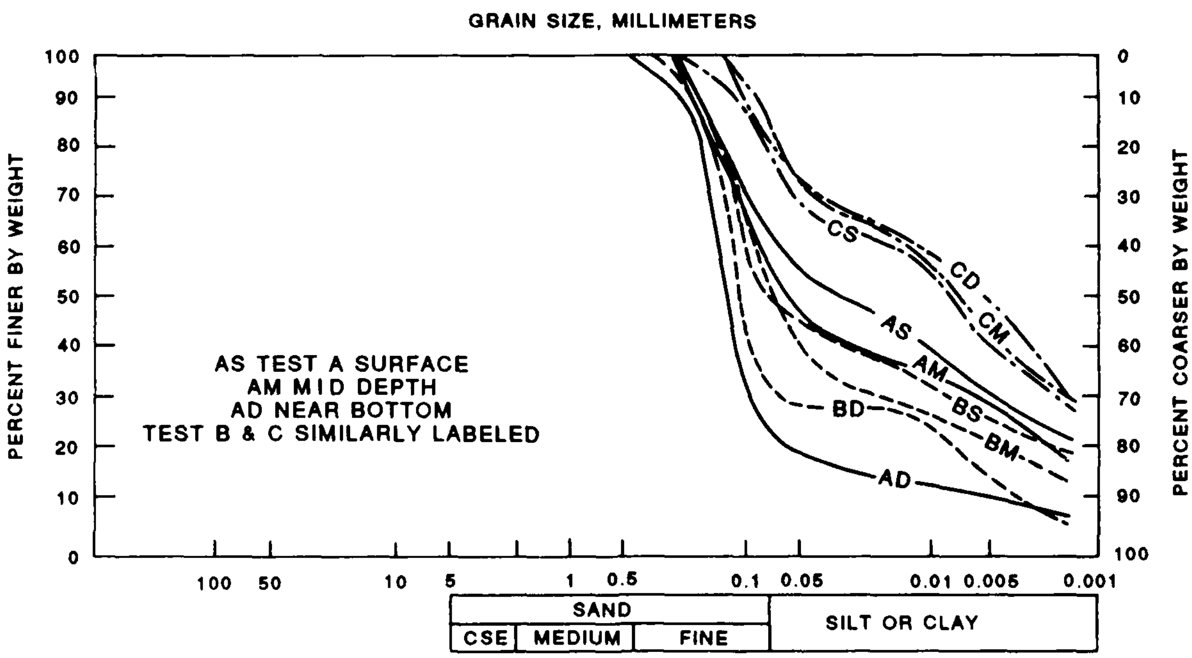
material were limited in number and are reflective of only the upper few feet of in situ sediment. Any material removed from the channel by clamshell at depths below those previously dredged would likely reflect the coarser grain size distribution of "new work" material.

Classification

29. Atterberg limits of the grab sample taken for this study are shown plotted on the plasticity chart in Figure 10. Also shown plotted in Figure 10 are the plasticity data for the samples of material taken from the loaded barges as described in the following paragraphs. The grain size data and Atterberg limit data were used to classify the material using the USCS. The maintenance sediments dredged during this study are classified as a fat clay (CH) with traces of sand.



a. Barge overflow samples and in situ channel sediments



b. In-barge sediment materials

Figure 9. Grain size distributions

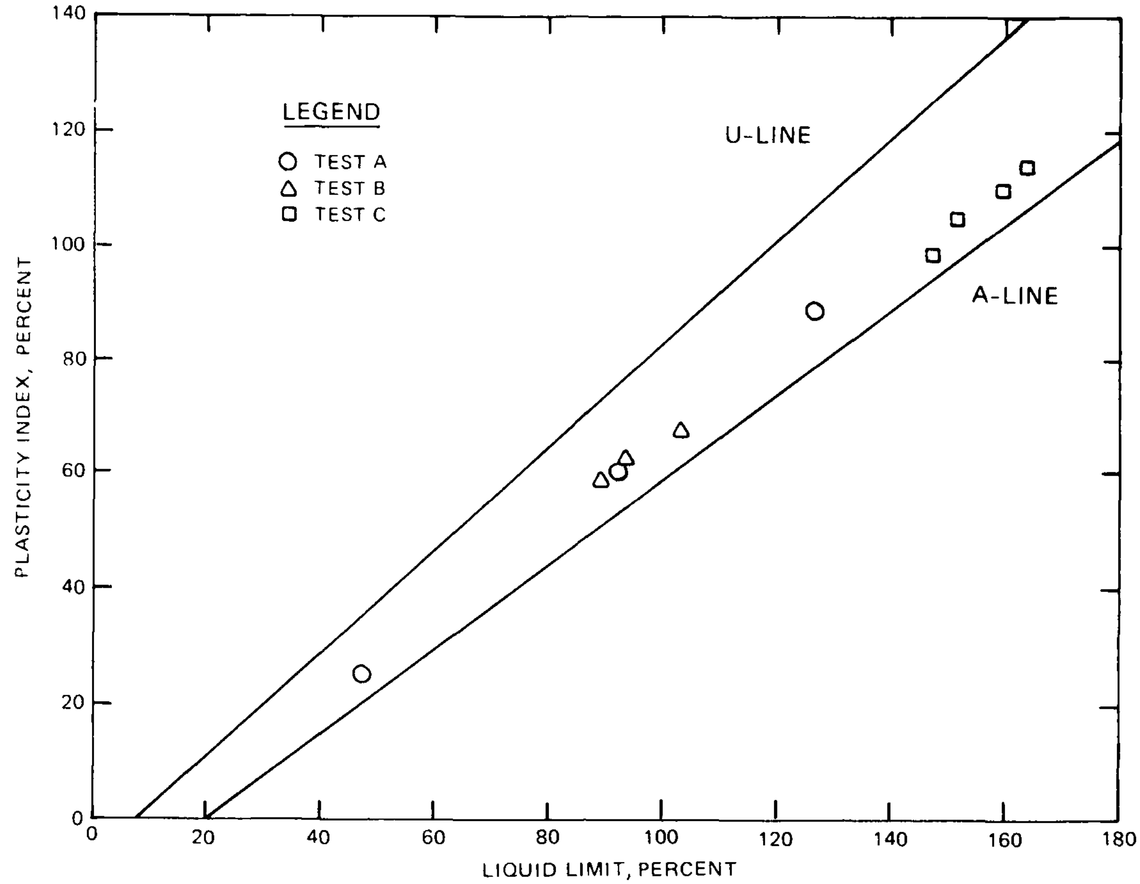


Figure 10. Plasticity chart

Characteristics of Material in Loaded Barges

Visual observations

30. As loaded buckets were raised above the water surface, some leakage of material from the lips of the bucket and spillage from the top of the bucket was observed. The load in the buckets varied by bucket load. Some of the loads were heaped well above the top of the bucket with clumped material and had a minimal volume of entrapped water. Others were not heaped, and a portion of the bucket load was entrapped water. As the buckets were placed into the barge, the relative volume of water in each load could be seen. For all bucket loads, the loads were visually stiff near the bottom of the bucket and progressively looser near the top of the bucket. For some loads, a sand layer was clearly visible at the bottom of the bucket, indicating the bucket had penetrated past the depth of previous dredging into "new work" material.

31. As the barges were filled, a surface layer of slurrylike material accumulated in the barges. Once the barge filling progressed past a quarter to half full, portions of bucket loads that were clumped would quickly disappear beneath the surface. Since there was no visible mounding of clumped material above the slurry surface, the slurry layer had accumulated to an apparent depth of at least several feet once the barges were filled to the point of overflow.

32. Once the barge had been filled to the top of the coaming, the nature of the near-surface portion of slurry layer could be determined. A surface layer of slurry with waterlike consistency a few inches thick was evident. Below this, the layer was viscous to the feel, with soft clay balls suspended in the slurry. This indicated that the densest portions of the clamshelled material were accumulating on the bottom of the barge. The entrained water was displaced to the surface, mixing with soft clay balls and forming the slurry layer. When overflow began, the thin surficial slurry layer overflowed first, followed by the more viscous slurry and clay ball mixture.

Sampling and testing

33. Immediately prior to initiation of overflow for each test barge, samples of the material in the barges were taken using a sampler consisting simply of a polyvinyl chloride pipe section with end-stoppers attached to a pole. The sampler was lowered to the desired sampling depth and opened to retrieve a sample. Samples were taken from the near-bottom, middepth, and within 2 ft of the surface of the material in the loaded barges immediately prior and during the overflow period. These samples were analyzed for water content, Atterberg limits, and grain size.

34. As mentioned above, a nuclear density probe was also used to obtain a density profile in the loaded barges immediately prior to overflow and following completion of overflow for Tests A and B.

Solids concentration

35. Results of solids concentration profiles of the barge samples are shown in Table 2. The trend of solids concentration with depth of material in the barges showed an increase from near-surface to middepth and from middepth to bottom for all three tests. This same trend of steadily increasing density with depth was observed in the nuclear probe data. The solids concentration values for barge samples in Tests A and B are comparable to the values for

Table 2

Solids Concentrations of Barge Samples

Depth of Barge Sample ft (m)	Solids Concentration, g/ℓ		
	Test A	Test B	Test C
1.5 (0.5)	300	392	252
10 (3.0)	402	445	374
20 (6.0)	727	585	427
Average	476	474	351

solids concentration calculated from the measured densities by nuclear probe. These data are shown plotted with the nuclear probe data in Figures 5 and 6.

36. The average solids concentrations of material in the loaded barges based on the barge samples were 476, 474, and 351 g/ℓ for Tests A, B, and C, respectively. These values indicate that material in the loaded barges has an average density comparable to that in the lower layers of the in situ sediment.

37. Solids concentrations from samples taken for Test C are inconsistent with the barge displacement data. Total load in the barge as determined from draft was the highest of the three tests, while the solids concentration in the barge determined from the samples was the lowest. A possible explanation of this result is that the barge samples were not representative of the density of the total load for Test C. Inaccuracy in measurement of displacement could also account for some of the difference.

Grain size distribution

38. Grain size data from the barge samples are shown in Figure 9b. Grain size data from the in situ channel core and grab samples (Figure 9a) fall within the broader grain size range for all barge samples. The data show that the material as placed in the barges is approximately 41 percent sand and has an average grain size of approximately 0.04 mm. The material in Test C was finer than that in Tests A and B, with approximately 22 percent sand.

39. For all three tests, the grain size distribution was progressively coarser with depth of sample. This indicates that some sorting of coarser sand particles within the barges occurred. It is possible that some settling

of sand particles occurs within the more fluid upper layers of material. Another explanation is that the more fluid portions of the material as excavated by the mechanical dredge, which are displaced to the upper layers in the barge, are composed of a finer range of grain sizes.

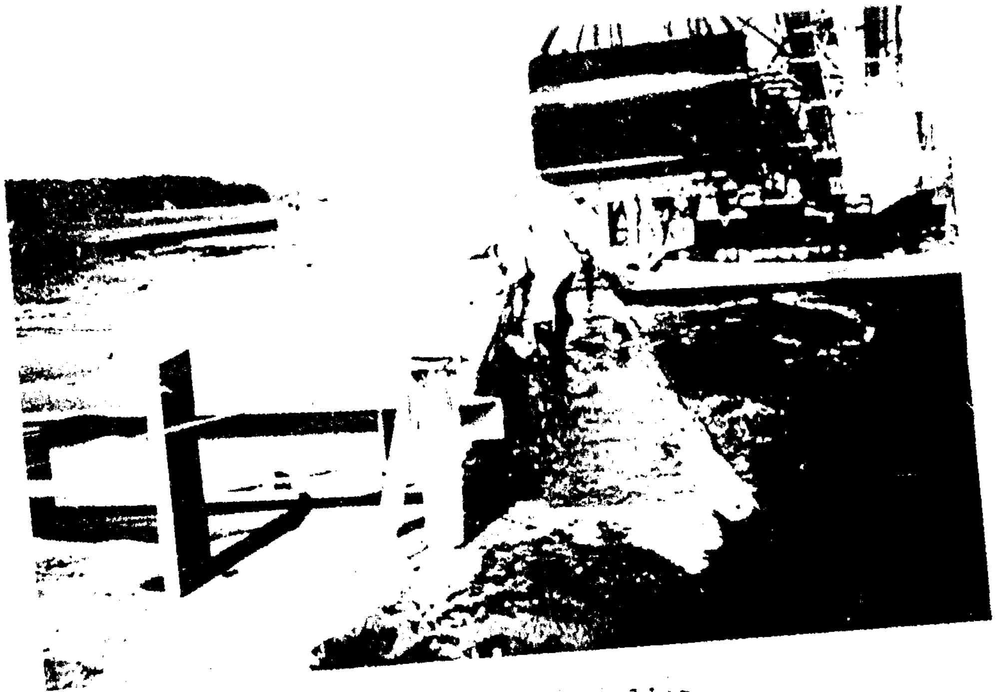
Overflow Characteristics

Visual observations

40. At the initial point of overflow, a thin surficial slurry layer containing no clay balls overflowed first. This surficial layer had completely overflowed within 1 to 2 min due to the placement of the first one or two bucket loads past the point of overflow for all tests. As additional loads were placed, a more viscous slurry and clay ball mixture was evident in the overflow. Clay balls could be clearly seen spilling over the coaming. These balls were very soft and were suspended in the more viscous slurry. As overflow progressed, the concentration of the slurry and the relative concentration of clay balls increased. After a period of approximately 5 min, an accumulation of clay balls at the edge of the coaming was observed, as shown in Figure 11a. This formed a "dam" of sorts, which tended to build up a head of slurry above the edge of the coaming. Near the end of the overflow period, the concentration of the overflow was observed to be much higher than at the initial point of overflow, and the overflow contained a high concentration of suspended clay balls.

Sampling and testing

41. Samples of the overflow were taken by directly filling wide-mouth 1-ℓ sample containers at timed intervals during the overflow event. The sample containers were filled with a composite sample of the overflow along the entire length of barge coaming involved with the overflow. This was accomplished by filling the sample container while walking along the coaming, as shown in Figure 11b. The filling procedure was accomplished such that the volume of composite overflow sample taken from various points along the coaming was judged to be in proportion to the relative flow rate of the overflow at those points. This provided the most representative sample possible. During the sampling, a conscious attempt was made to representatively catch both clay balls and slurry. For Test A, samples were taken at 5-min intervals, and only three samples were taken before the dredge operator



a. Overflow sampling

b. Loaded barge following overflow

Figure 11. Barge overflow sampling

elected to stop overflow. For Tests B and C, an effort was made to take samples as quickly as possible, and samples were taken at approximately 2-min intervals, yielding five and eight samples, respectively. The overflow samples were analyzed for solids concentration and grain size.

Solids concentration

42. The solids concentrations of the overflow samples are shown in Figure 12. This figure shows that the solids concentration of overflow increased with time of overflow. This indicates that as filling continued past overflow, the surficial layers of material were displaced by the denser portions of the bucket loads. Since the density of material in the barges increased with depth, the overflow concentration increased as progressively deeper layers were displaced. For Tests B and C, an overflow sample was collected at the start of overflow. The average overflow concentration at the start of overflow for these tests was 88 g/ℓ. The average concentration for all three tests at the end of overflow was 248 g/ℓ. As shown in Figure 12, the apparent maximum concentration of overflow was 200 to 300 g/ℓ, roughly equivalent to the average in situ sediment concentration.

Grain size distribution

43. Grain size data from the overflow samples are shown plotted in Figure 9a. The overflow material was approximately 15 percent sand and had an average grain size of approximately 0.004 mm. As with the in-barge material, the grain size distribution of overflow material in Test C was finer than that in Tests A and B. The grain size distributions of the overflow samples show less variability and finer grain size as compared with the range of in-barge samples. The finer grain size of overflow reflects the fact that grain size of the in-barge material is finer in the upper layers.

44. As described previously, either some sorting of coarser sand particles within the barges occurred or the more fluid portions of the excavated material that comprise the overflow had finer grain sizes initially.

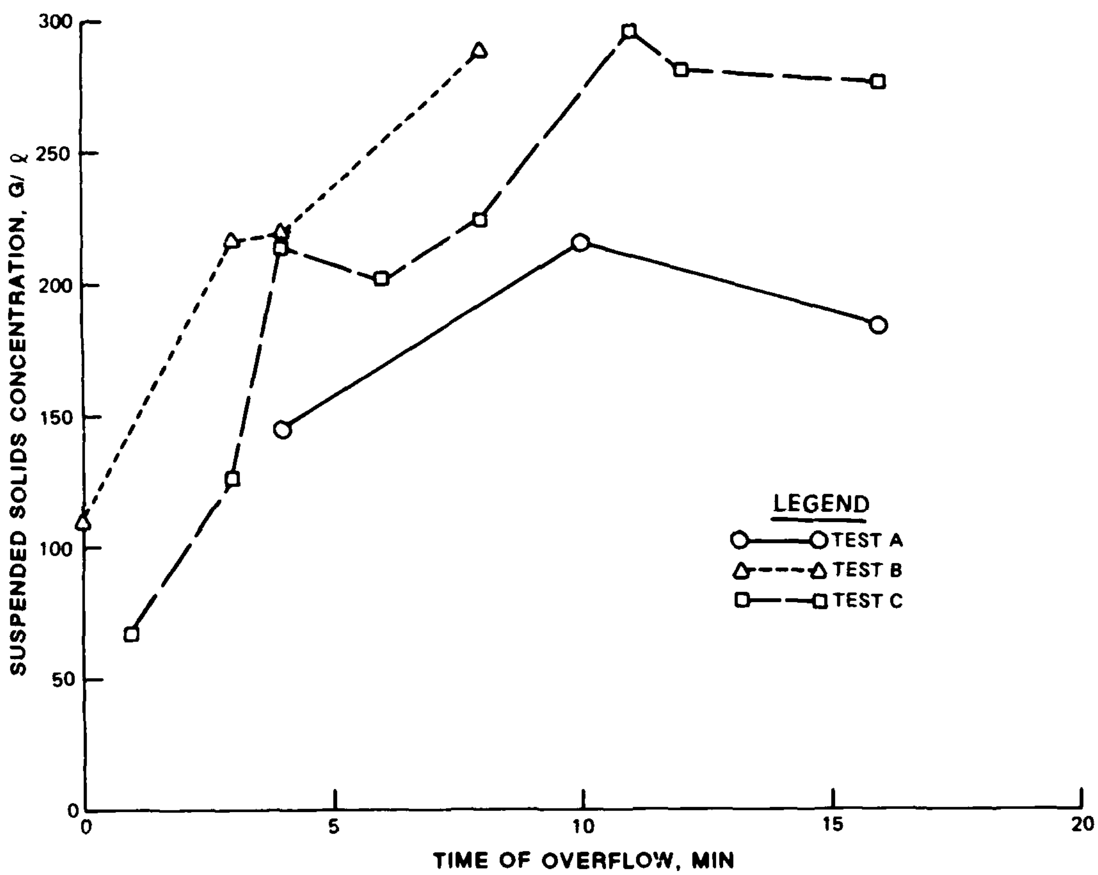


Figure 12. Solids concentrations of overflow

PART IV: CHARACTERIZATION OF SUSPENDED SEDIMENT PLUMES

45. Plumes formed at the MOTSU dredging site as a result of sediment resuspension by dredging and by intentional overflow from scows during testing. A resuspended sediment plume of some magnitude is formed at virtually all dredging sites. Near the sediment release or discharge point, plumes can be visually distinct and self-organized, and can exhibit dynamical behavior due to density differences with the ambient. As mixing occurs with distance from the discharge point, plumes lose their distinctive character and merge with the ambient suspension.

46. This part presents hydraulic transport data collected at the MOTSU overflow dredging site and results of analyses to characterize suspended sediment plumes resulting from dredging and overflow activities. The objectives of the plume sampling and analysis were to:

- a. Document the magnitude of plume suspended material concentrations and turbidities for both dredging and dredging plus overflow operations.
- b. Estimate the fraction of the materials that escaped from the proximity of the discharge.
- c. Describe suspended materials transport characteristics away from the dredging site.

To meet these objectives, plumes were sampled from a grid of fixed locations and from locations at varying distances from the operating dredge. An analytic framework is important to check the consistency of field measurements, to identify dominant field processes, and to fill in information gaps. The latter can be caused by difficult or impossible field sampling conditions. For example, field data on currents and concentrations near the operation were not extensive enough to directly integrate into transport rates. The sections that follow describe prototype measurements, analytic procedures, results of analyses, and a summary of plume characteristics.

Prototype Measurements

Visual observations

47. Plumes from dredge bucket spillage were observed to form as a series of intermittent patches advecting downcurrent. Spacing of these plume patches depended on the dredge bucket cycling time and the current speed. Plume

patches tended to spread, merge with each other, and mix with the ambient further downstream. The irregular spacing of these patches within the plume accounted for much of the variability in plume measurements.

48. Overflow plumes also formed in a patchy manner along the side of the disposal barge where overflow occurred. The barge overflow was intermittent as individual bucket loads were added to the barge. In addition, the duration of the overflow tests was short, which made the total length of the overflow plumes about the same length as the shortest sampling distance. The short, patchy nature of overflow plumes made reliable sampling difficult since, even at sampling locations 30 m from the barge, overflow plumes were already indistinct.

49. Spillage of sediment material from the clamshell bucket was estimated from visual observations. Geometries of the bucket in its open and closed positions were lifted from photographic and video images made in the field. Figure 13 shows a representation of the clamshell operation and the spillage resulting from changes in bucket volume. Based on these observations it was estimated that 20 to 30 percent of the sediment excavated from the bed was spilled before reaching the disposal scow. Based on the average dredging rate, this represents an actual sediment release rate of 27,500 to 41,500 g (dry)/sec.

Sampling methods

50. Plume sampling was performed September 24, September 30, October 20, and October 21, 1987. Overflow tests were conducted October 20-21, 1987. Plume water samples were taken 20 to 305 m downstream from clamshell dredging, and from simultaneous dredging and overflow activities. Background water samples were also collected at sampling stations upstream and downstream from dredging activities, as shown in Figure 2.

51. *In situ* turbidity instruments and fathometers were used to identify the extent of the plume and to aid in locating the plume sampling stations within the identifiable plume. Samples were taken at 0.6-, 4.5-, and 9-m depths, corresponding to near-surface, middepth, and near-bottom. However, due to the limited time available for sampling operations, samples were often taken at the 9-m depth only. A Van Dorn-type water sampler was used to collect samples. Water samples were analyzed for total suspended material as nonfilterable solids, using a standard method (Plumb 1981). Turbidity and salinity were also measured using the samples.

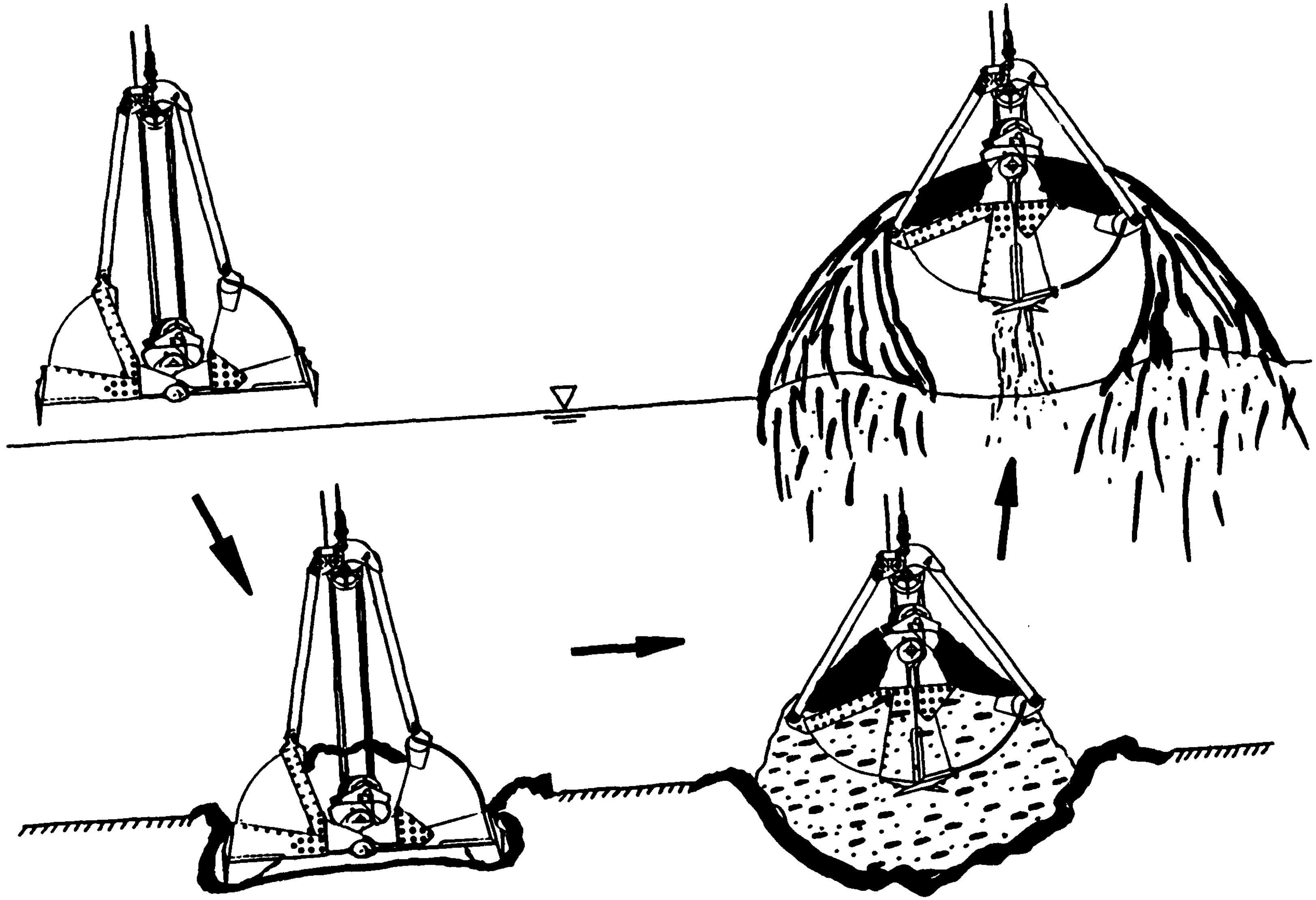


Figure 13. Schematic representation of clamshell bucket operation

52. Currents were measured from a boat using a profiling electromagnetic meter. An InterOceans Model S-4 was used to record time, depth, and current speed and direction on internal solid state memory. During current measurements, the sampling boat was moored to a buoy. Currents were taken about every 2 hr and interpolated to the time of the plume samplings.

Plume data

53. Of a total of 24 plume samplings, 22 were performed during dredging, and 2 were performed during dredging and overflow. The short duration of overflow operations limited sampling. Average total suspended material (TSM) was 65 mg/ℓ above background for the overflow plume samplings, compared with 47 mg/ℓ TSM above background for all plume samples. However, the difference between standard deviations for the dredging samples and the overflow test samples was greater than the difference between the mean values. The TSM values of the overflow plumes were not significantly different from those of the dredging plumes. The variation in the overflow plume samplings was great, but no greater than the variations in all the plume samplings taken together.

54. Eight plume vertical TSM profiles averaged 65 mg/ℓ above background. Sixteen other plume point samplings averaged 36.5 mg/ℓ TSM above background. All plume samplings together had an average TSM of 47 mg/ℓ above background. Background depth-averaged TSM values were about 40 mg/ℓ on September 24, 30 mg/ℓ on September 30, 14 mg/ℓ on October 20, and 10 mg/ℓ on October 21.

55. Turbidity measurements are summarized in Tables 3-7. These tables show background values and plume values with background turbidities removed, except for Table 7, for which no background readings were available.

56. Turbidities of all dredging plume samples averaged 6.2 nephelometric turbidity units (NTU) above background. A total of 73 plume samples were taken on September 24, September 30, and October 20. Turbidities for overflow tests on October 20 averaged 21.6 NTU above background for six samples. The difference between standard deviations for the dredging only samples (8.6 NTU) and the overflow test samples (15.7 NTU) was greater than the difference between the mean values. Mean values were therefore not significantly different.

57. Figure 14 illustrates turbidities at upcurrent and downcurrent water sampling stations (relative to the dredge from the clamshell dredge). Current measurements are also included. For September 30, station B1 was downcurrent, on flood tide, from 0900 through the end of the sampling day. Station B3 was

Table 3

Average Turbidities Taken September 24, 1987

Depth, m	Background Turbidity NTU (n)*	Plume (Background Removed), NTU, Measured at Distances Downstream		
		30 m	150 m	300 m
		Ebb Tide, Dredging Only		
1	7.1 (6)	14.2 (3)	--	1.7 (2)
4.5	8.0 (6)	1.8 (3)	--	-0.1 (2)
9	10.4 (6)	14.1 (3)	13.6	-1.9 (2)
		Flood Tide, Dredging Only		
1	4.0 (8)	8.8 (2)	2.8	4.8 (2)
4.5	7.3 (8)	7.7 (2)	1.5	2.4 (2)
9	9.9 (8)	12.1 (2)	-0.9	8.1 (2)

* Number of samples taken and averaged.

Table 4

Average Turbidities Taken September 30, 1987 (Flood Tide, Dredging Only)

Depth, m	Background Turbidity NTU (n)*	Plume (Background Removed), NTU, Measured at Distances Downstream		
		30 m	150 m	300 m
1	5.0 (21)	2.0 (3)	0.3 (3)	1.0 (3)
4.5	6.1 (21)	1.4 (3)	1.1 (3)	0.7 (3)
9	8.9 (21)	5.2 (3)	8.8 (3)	10.8 (3)

* Number of samples taken and averaged.

Table 5

Average Turbidities Taken October 20, 1987 (Ebb Tide, Dredging Only)

Depth, m	Background Turbidity NTU (n)*	Plume (Background Removed), NTU, Measured at Distances Downstream		
		30 m	150 m	300 m
1	3.9 (2)**	3.2	6.9 (2)	5.5 (2)
4.5	8.1 (2)	3.9	16.4 (2)	1.8 (2)
9	8.9 (2)	32.1	32.6 (2)	0.2 (2)

* Number of samples taken and averaged.
** Collected 250 m upstream of the dredge.

Table 6

Average Turbidities Taken October 20, 1987

Depth, m	Background Turbidity NTU (n)*	Plume (Background Removed), NTU, Measured at Distances Downstream		
		30 m	150 m	300 m
	Ebb Tide, Dredging and Overflow (1130 EST)			
1	3.9 (2)**	1.9		
4.5	8.1 (2)	19.9		
9	8.9 (2)	49.1		
	Flood Tide, Dredging and Overflow (1540 EST)			
1	3.2†	14.8		
4.5	6.0	18		
9	13.0	26		

* Number of samples taken and averaged.
** Collected 250 m upstream of the dredge.
† Collected 60 m upstream of the dredge.

Table 7

Average Turbidities Taken October 21, 1987

Depth, m	Plume NTU Measured at Distances Downstream	
	0 m*	30 m
	Ebb Tide, Dredging Only	
1	58.5 (2)**	55
4.5	42	27
9	12	42
	Ebb Tide, Dredging and Overflow (1405-1414 EST)	
1	77.3	
4.5	17	
9	150	

* Taken at the downstream corner of the dump scow.
** Number of samples taken and averaged.

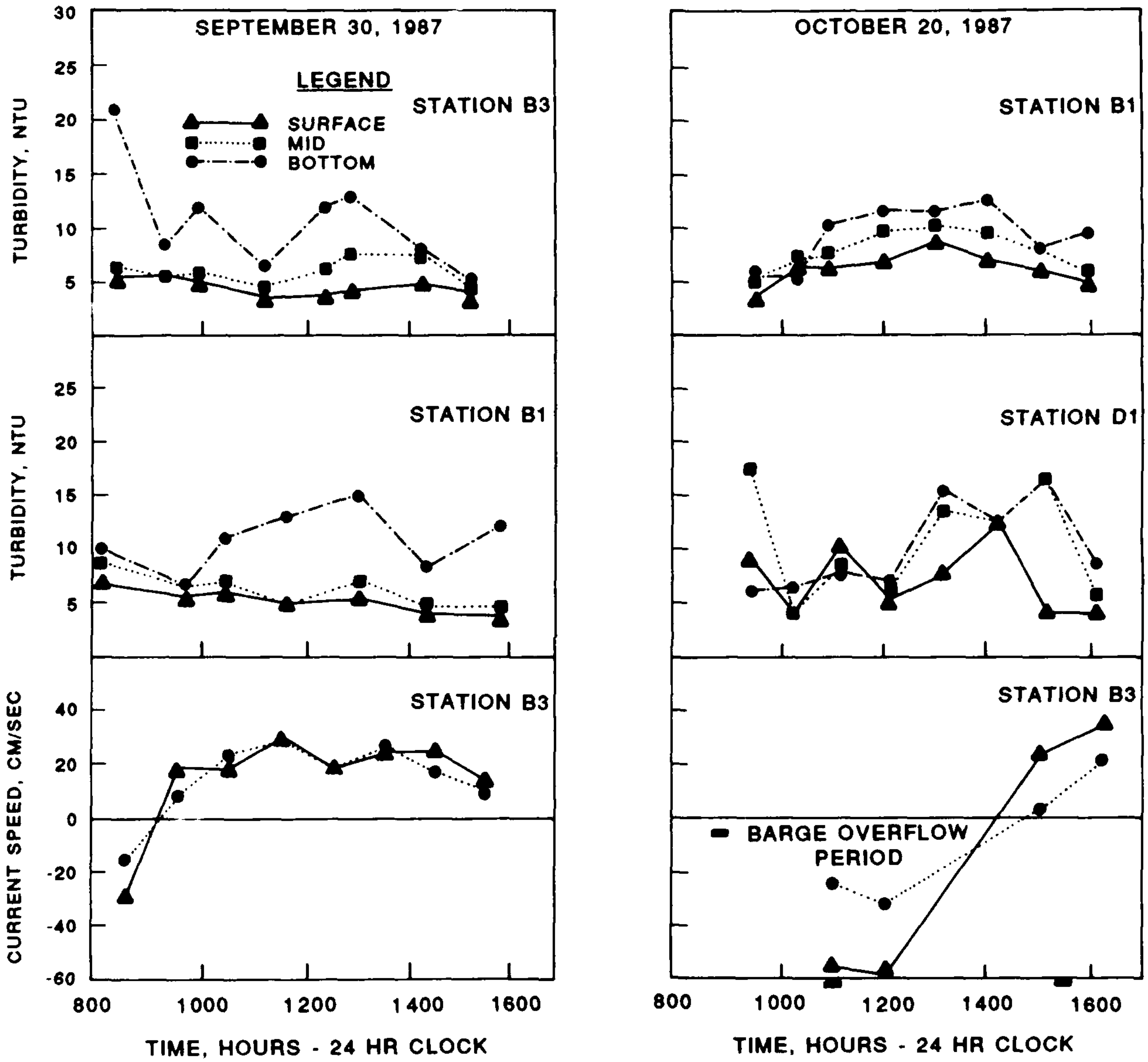


Figure 14. Turbidities measured upcurrent and downcurrent of a clamshell dredge. Measurements of September 30 are dredging only, while those of October 20 include two barge overflow periods as indicated. Current speed and direction are also shown

upcurrent of the dredge for that same period. Differences between upcurrent and downcurrent turbidities for September 30 (a dredging day) were generally less than 5 NTU. For October 20 (a dredging and overflow day), station B1 is upcurrent, on ebb tide, and station D1 is downcurrent of the dredge for the majority of the sampling day. Station D1 exhibited fluctuations in turbidity that may be due to dredge-induced perturbations. Station D1 was within 300 m of the dredge, and the fluctuations may reflect patchy near-field phenomena not seen in the comparison of September 24, where the down-current stations were between approximately 550 and 900 m down-current (Payonk, Palermo, and Teeter 1988).

Settling tests

58. For the purposes of estimating hydraulic transport of estuarine fine-grained sediment material, settling velocity is a better characterization than dispersed grain size. Settling rates of fine-grained estuarine sediments vary with concentration: usually constant below a certain concentration, increasing sharply up to another concentration, and hindered at still higher concentrations. A sample of bed sediment from the vicinity of the dredging operation was tested for settling rates.

59. A 1.85-m-high by 10-cm-diam clear plastic tube was used for the testing. Four tests were performed at progressively higher initial concentrations of from 42 to 338 mg/ℓ. The sediment was suspended in seawater, mixed, allowed to settle overnight, and then remixed for 5 min before beginning the tests. Samples were withdrawn from 10 cm above the tube bottom at 1, 7, 15, 30, 45, 60, 90, 120, 180, 250, and 360 min after initiation of the tests. Samples were analyzed for TSM, and the results were used in regression models to describe the distributions of settling rates.

60. Results are shown in Figure 15 plotted as median settling velocity versus concentration. Although the number of test points was small, the break between constant and enhanced settling regions was identified, based on the consistency of previous tests, to be about 110 mg/ℓ. Settling rates decreased slowly below this concentration. The slope of the enhanced settling region was found to conform to the commonly observed value of four-thirds.

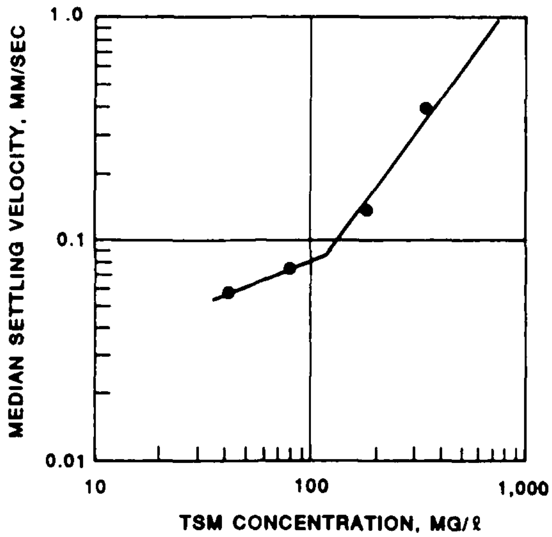


Figure 15. Relationship between settling velocity and TSM concentration

Analytic Procedures

Conceptual framework

61. Three distinct dispersion stages occur for dredged sediment plumes. These are defined as follows:

- a. Initial descent of a dense plume to the bottom and entrainment.
- b. Bottom spreading, settlement of heavy materials, and development of a passive plume.
- c. Merging of the passive plume with natural sediment fields.

62. During stage 1 of plume dispersion, dredged material descends quickly to the bed due to density effects. Dredged material is high in solids, and a dense plume is formed as the material enters the water. Buoyant and dense plumes have been well studied under laboratory conditions, and previous results can be used to evaluate dredged sediment plumes.

63. During density-driven descent, dredged material is diluted by the entrainment of ambient water into the plume. Thus, during descent the plume volume flux (Q_f) increases along its trajectory (s) toward the bottom. Various (similar) relationships and expressions have been used to describe this process, for example:

$$\frac{dQ_f}{ds} = 2\pi\alpha b U_m \quad (1)$$

where

α = entrainment coefficient

b = local width

U_m = center-line plume velocity

Entrainment coefficients vary somewhat with densimetric Froude number (Fn):

$$Fn = \frac{Q_o}{A\left(\frac{gD\Delta\rho}{\rho_a}\right)^{1/2}} \quad (2)$$

where

Q_o = overflow discharge rate

A = area of the discharge

g = acceleration of gravity

D = characteristic width

$\Delta\rho$ = initial density difference between the plume and the ambient density (ρ_a)

Thus, lower entrainment coefficients are found for lower Froude numbers, and higher Froude numbers indicate the creation of a jet.

64. Sediment characteristics can also affect entrainment coefficients and rates. As moisture contents approach the liquid limits of the material, entrainment rates have been found to decrease rapidly and approach zero.

65. Entrainment results in dilution of overflow plume concentrations. Average dilution ($\bar{S}$) is defined as

$$\bar{S} = \frac{C_o - C_a}{C - C_a} \quad (3)$$

where

C = concentration at some point and time

o,a = subscripts which indicate initial plume and ambient concentrations, respectively

66. Plumes behave actively while they possess an appreciable density difference with the ambient. Initial density difference causes a density-driven descent of the plume toward the bed. Mixing with the ambient is rapid during

descent. Initial mixing substantially reduces density differences with the ambient. The five variables that affect the dynamic behavior of suspended sediment plumes are the volume rate of the discharge (Q_o), the initial density difference between the overflow material and the ambient ($\Delta\rho$), the water depth (H), the current speed (U), and the vertical density gradient ($d\rho/dz$). Some material is sheared off the plume during descent, and some is diluted to the extent that ambient currents immediately redisperse material from near the bed.

67. During stage 2 of overflow dispersion, the remaining diluted sediment material encounters the bed, then spreads along the bed as a result of momentum and $\Delta\rho$. The thickness and rate of spreading of the material will depend on the dilution at the end of plume descent, the density difference with the ambient, the ambient flow, and the viscosity of the material. Only very crude analytical procedures are available to predict bottom spreading for an idealized situation such as a flat, unbounded case. Prototype situations in tidal flows are generally very complex.

68. Stage 3 of overflow dispersion results as sediment materials are mixed by turbulent diffusion into the flow, form fluid mud layers at the bed, or permanently deposit to form a new bed. Within a matter of minutes of overflow, the portion of plumes remaining in suspension behaves passively and is transported by the ambient flow, depending on sediment characteristics. The ability for natural turbulent diffusion to mix the material into the flow depends on the level of turbulent mixing in the flow and the settling properties of the material.

Plume dynamics and mixing

69. Plume mixing and trajectories are very difficult to gage in the field due to lack of visibility in the water, the presence of the barge, and variabilities in the ambient conditions. Near-field sampling of plumes within about 10 to 20 m of the discharge is extremely difficult and was not attempted during the MOTSU overflow study. Plume analyses were performed and reported in this section to describe important plume behavior, namely mixing and plume trajectory.

70. Analytic methods were used to evaluate the descent and initial mixing of plumes. The methods presented by Teeter (1979) were used in the analysis. Brooks (1973) also presents analyses for plumes in stagnant ambients. Suspended sediment releases formed negatively buoyant plumes, which are

dynamically analogous to, though the geometric inverse of, buoyant wastewater discharges made at the bed. The five variables that affect the dynamic behavior of suspended sediment plumes are the volume rate of the discharge (Q), the initial density difference between the discharge and the ambient ($\Delta\rho$), H, U, and the vertical density gradient ($d\rho/dz$).

71. Overflow plumes formed along the side of the barge parallel to the current, equivalent to a point discharge. Had the side of the barge been perpendicular to the flow, the discharge would have resembled a line discharge. Ambient density stratification was calculated from salinity and temperature profiles. The Cape Fear estuary in the vicinity of MOTSU was in a well-mixed condition during the field study. Vertical density stratification was slight, but was found to affect plume descent and mixing somewhat. Current speeds had a greater effect on predicted plume behavior. For the mean conditions encountered during this study, the expression

$$\bar{S} = 0.9\ H\left(\frac{U}{Q}\right)^{2/3}\left(\frac{\Delta\rho}{d\rho/dz}\right)^{-1/3} \tag{4}$$

describes dilution as the plume reaches the bed, where $\bar{S}$ is the average dilution value. The units of metres, kilograms, and seconds are used.

<u>Plume transport rate</u>

72. Plume sampling data were used to estimate plume suspended sediment transport rates. Transport rates are suspended sediment flux rates away from the discharge point, and therefore represent apparent suspended sediment release rates. Much of the material spilled from the dredge bucket or released in barge overflow consisted of sediment agglomerates or clumps that rapidly sank without going into suspension. In addition, larger sediment particles, such as coarse silts and sands, settled and deposited rapidly and were not transported far from their release points. Plume transport rates include only that portion of the spillage and/or overflow actually in suspension at some distance away from the release point. The significance of the plume transport rate is that it represents the potential for general suspended sediment effects away from the dredging site.

73. Field data on currents and concentration were not extensive enough to directly integrate into transport rates. Estimates of plume transport rate were made assuming that samples were taken along the plume center line, that

plumes could be described in a depth-averaged manner, and that deposition did not occur. An inverse technique was employed using an analytical plume model as a basis. Data on TSM, currents, and distances downstream were used to calculate a plume transport rate for each sampling. A two-dimensional, vertically averaged analytical model of the spread and deposition of a suspended sediment plume was the basis for the analysis. The model equation was

$$C = \frac{Q_s}{2HV_sX} \exp\left(- \frac{UY}{V_sX} - \frac{PW_sX}{HU}\right) \tag{5}$$

where

C = depth-averaged plume concentration at X and Y

Q_s = sediment release rate, kg/sec

H = depth, m

V_s = dispersion velocity, m/sec

X,Y = arbitrary coordinates in the downstream and cross-stream directions, m

U = depth-averaged current speed in the X-direction, m/sec

P = depositional probability

W_s = settling velocity, m/sec

By assuming that samples were taken along the plume center line ($Y = 0$), that current velocities were such that for fine sediments $P = 0$, and that V_s was 11 percent of U, Equation 5 was rearranged to calculate Q_s values from the field data. The Q_s values estimated from plume measurements taken 20 to 305 m from plume sources were estimates of transport rates. Currents were interpolated to the time of suspended sediment samplings from 2-hr readings.

Vertical plume stratification

74. The overall ability of the turbulent flow to mix overflow sediment materials is related to the balance between turbulent mixing and settling processes. The particle Peclet number (Pe) expresses this ratio:

$$Pe = \frac{W_sH}{Kz} \tag{6}$$

where Kz is the vertical eddy diffusivity, in square centimetres per second. The vertical eddy diffusivity under neutral (homogeneous) density conditions (Kz_o) can be approximated by the flow depth (H) and shear velocity (U_*) by

$$Kz_o = 0.067U_*H \tag{7}$$

However, under stratified conditions, Kz values are reduced as a function of gradient Richardson number (Ri) and can be approximated by

$$Kz = Kz_o(1 + 3.33\ Ri)^{-1.5} \tag{8}$$

At low suspended sediment concentrations, Ri values in estuaries depend predominantly on vertical salinity gradients. Where high suspended sediment concentrations exist, Ri values also depend on vertical suspension concentrations, as discussed later.

75. Experiments indicate that suspensions cannot be maintained by turbulent mixing when $Pe > 6\text{-}10$. If concentrations and hence W_s values are high, sediments may leave suspension and form fluid mud layers at the bed. Thus, the process of vertical turbulent mixing may limit the escape of sediment materials from an overflow site. If appreciable material is sheared off the dense plume, concentrations, settling rates, and Peclet numbers are increased, and deposition from suspension increases. Additional analyses and information on rheological properties of the fluid mud must be applied to determine whether the fluid mud layer will flow or become stationary.

76. A fluid mud layer, flowing or stationary, formed at the bed will be accompanied by a lutocline, a strong vertical density discontinuity, at the interface with the overlying flow. Vertical mixing will decrease at the level of the lutocline analogous to the salinity stratification situation, and expressed in Equation 8. Because of the magnitude of the density change, the lutocline will strongly reduce vertical turbulent exchange between the fluid mud layer and the overlying flow.

Statistical analyses

77. Correlation coefficients were computed for the matrix of variables: distances from the dredge, plume depth-averaged TSM concentrations, depth-averaged current speeds, and calculated transport rates.

78. Plume TSM and computed transport rate data were fit to various statistical distributions. Statistical distributions are of practical importance. Certain central tendencies and peak values are often used to judge the characteristics of water masses in terms of their suitability as a medium for

living organisms. Normal, log-normal, and Weibull (a special case of the logarithmic) distributions were used.

Results of Analyses

Plume dynamics and mixing

79. Average overflow plume conditions were as follows:

$Q = 0.28$ cu m/sec

$\Delta\rho = 140$ kg/cu m

$H = 11$ m

$U = 0.25$ cm/sec

$d\rho/dz = 1.0$ kg/cu m/m

80. An average $\bar{S}$ of 49 was predicted, and descent was predicted to be to the bed for average conditions. The expected TSM at the bed would have been about 4 g/ℓ given the average overflow TSM. As noted above, clumps settled out of the plume, and actual plume concentrations slightly downstream from the barge would be correspondingly less.

Plume transport rate

81. Calculated plume transport rates averaged 2.5 kg/sec using data from the eight vertical samples, and 2.2 kg/sec using data from the 16 spot samples. Plume transport rate estimates averaged 2.3 kg/sec taken together. Dredging and dredging plus overflow plume sampling results were similar and both had variabilities of about 100 percent. This suggests that the overflow sediment release rates were of the same order of magnitude as spillage, and that the total sediment release rates for dredging and overflow were probably on the order of 100 kg/sec. However, the sediment spillage rates from the dredge bucket were not determined directly. Average plume transport rates were only 2 to 4 percent of overflow sediment discharge rates (53 to 65 kg/sec, see Part III), implying that transport rate estimates are low, that most sediments were deposited within 30 m of the release or discharge points, or that much of the plume was unsampled.

Vertical plume stratification

82. The settling tests indicated that, at concentrations over 110 mg/ℓ, enhanced settling occurs. Plume analysis indicated that near the bottom, close to the overflow barge, concentrations could have been about 4 g/ℓ. Normally, enhanced settling continues with increasing concentration up to

about 1 to 10 g/ℓ. Using the smaller value, maximum Ws values would be expected to be about 2 mm/sec. The value of Kz was estimated to be about 74 cm^2/sec for average current conditions and assuming homogeneous density conditions. Thus, the Pe for the suspension resulting from overflow was estimated to be about 2.85.

83. The vertical distribution of a suspension for Pe = 2.85 was computed using methods described by Teeter (1986) (Figure 16). As shown in Figure 16, overall suspension stratification was predicted to be quite pronounced, much greater than was generally observed over the range of sampling depths. Near-bed samplings were generally at the 9-m depth, while overall H was 11 m. Thus, at 20 percent above the bed, Figure 16 predicts that concentrations are only 14 percent of the maximum near-bed value. Maximum concentrations must be sampled very near the bed, using procedures other than those available for this study, such as bottom-mounted tripods. Plume analyses indicated that samples taken during this study gaged water column effects, but not benthic effects.

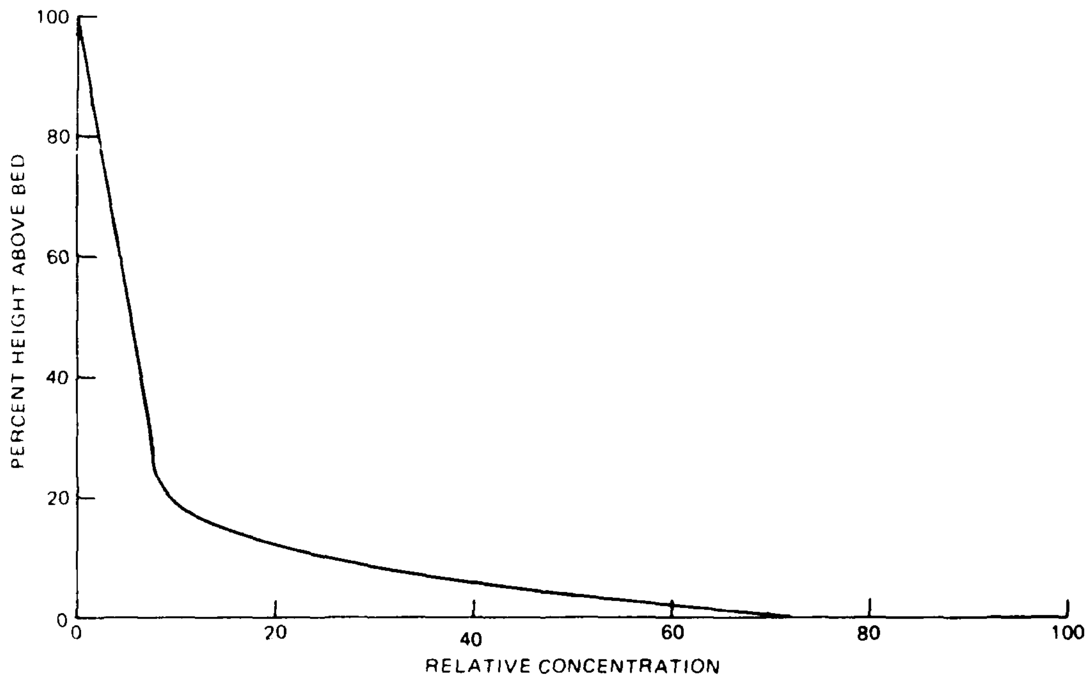


Figure 16. Vertical suspension stratification for Pe = 2.85

Statistical analyses

84. No important statistical correlations were noted between the variables: distances from the dredge, plume depth-averaged TSM concentrations, depth-averaged current speeds, and calculated plume transport rates. The best correlation found (0.48) was between plume TSM values and plume transport rates.

85. Both TSM and plume transport rate values were log-normally distributed (Figure 17). Therefore, median values are better measures of central tendency than mean values, and are as follows:

Value	TSM, mg/ℓ	Plume, kg/sec
Median	24.5	0.9
25th	12	0.4
75th	61	3.5

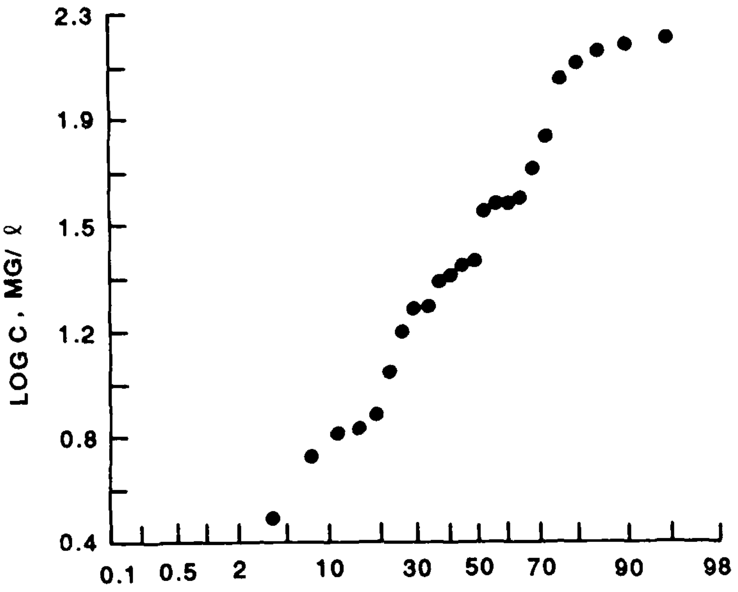
Coefficients of variation (standard deviations divided by means) were about 100 percent for both variables.

Summary of Plume Characteristics

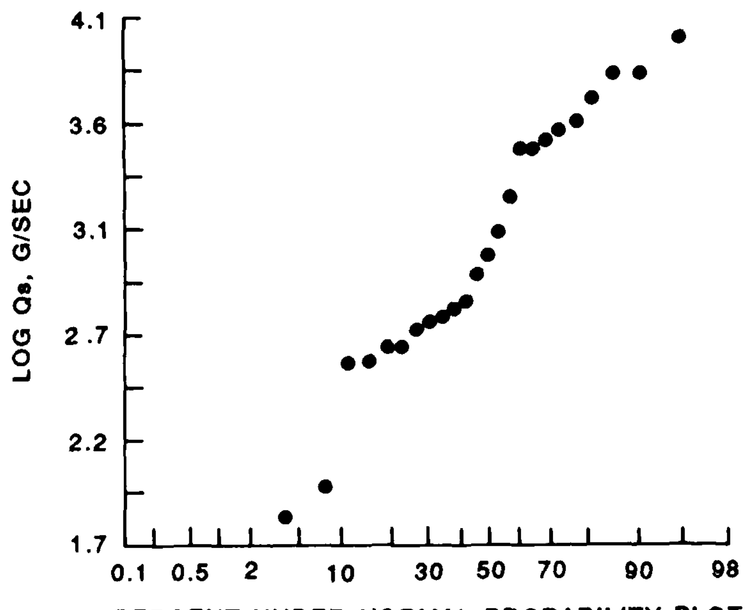
86. The short and patchy nature of overflow plumes made reliable field sampling difficult since, even at locations 30 m from the barge, plumes were already indistinct. Field sampling was restricted to the main portion of the flow and neglected near-bed zones.

87. Background depth-averaged TSM values were about 40 mg/ℓ on September 24, 30 mg/ℓ on September 30, 14 mg/ℓ on October 20, and 10 mg/ℓ on October 21. Most of the plume samplings were performed during dredging only, and only a few were performed during dredging and overflow. Average TSM was 65 mg/ℓ above background for the overflow plume samplings, compared with 47 mg/ℓ TSM above background for all plume samples.

88. The sum of the standard deviations for the dredging-only samples and the overflow test samples was greater than the difference between the mean values. The TSM of the overflow plumes was not significantly different from those of the dredging-only plumes. The variation in the overflow plume samplings was great, but no greater than the variations in all the plume samplings taken together.



a. Plume TSM



b. Plume transport rates

Figure 17. Probability distributions for plume TSM and plume transport rates

89. The actual sediment release rates from the overflow were estimated from the overflow samples and records of the dredging rate. Actual overflow sediment release rates averaged 53,000 to 64,000 g/sec for the three overflow tests (see Part III). Sediment spillage rates from the dredge bucket were not measured. However, spillage rate estimates of 20 to 30 percent of the barge loading rate would have resulted in actual sediment release rates of 27,500 to 41,500 g/sec. Based on dredge observations, spillage rates of these magnitudes are considered to be possible. Therefore, sediment spillage rates from the dredge bucket are probably 50 to 75 percent of the actual sediment release rates from the overflow, and the total sediment release rates during dredging and overflow were probably on the order of 100,000 g/sec.

90. Calculated plume transport rates averaged 2.5 kg/sec using data from the eight vertical samplings, and 2.2 kg/sec using data from the 16 spot samplings. Plume transport rate estimates averaged 2.3 kg/sec taken together. The median value was 0.9 kg/sec and is more meaningful than the average value. Dredging and dredging plus overflow plume sampling results were similar and both had variabilities of about 100 percent. This suggests that the overflow sediment release rates were of the same order of magnitude. Calculated plume transport rates were only 2 to 4 percent of overflow sediment discharge rates (53 to 65 kg/sec). Thus, calculations underestimated transport rates, most sediments were deposited within 30 m, or much of the plume was unsampled.

91. An analysis of the descent and mixing of the suspended sediment plumes indicated that plumes would generally descend to the bed and mix to about 4 g/ℓ during initial descent.

92. Suspension stratification was predicted to be great for the region of the water column below the location where near-bed samples were taken, between the 9- and 11-m depth. Therefore, field sampling did not capture that portion of the suspended sediment in transport near the bed. Sampling this region is problematic and would require bottom-mounted near-bed sampling devices, unavailable for this study. Plume sampling for this study was representative for water-column suspended sediments, but not for local benthic effects.

PART V: EVALUATION OF BIOLOGICAL RESPONSES

General

93. Clamshell or bucket dredging introduces sediments into the water column through several mechanisms. Sediments are suspended by the action of the bucket or clamshell upon impact on the bottom, through erosion of the load during lifting and after breaking the surface of the water, and through leakage from the bucket. If barge overflow is practiced, the overflow introduces additional material into the water (see reviews in Barnard 1978; Lunz, Clarke, and Fredette 1984; Tavolaro 1984; LaSalle et al., in preparation).

94. While it is not yet possible to predict exactly the spatial and temporal changes in suspended sediment concentrations for a particular dredging project, numerous field studies suggest that patterns are discernible. The following is presented as a conceptual model against which the MOTSU dredging operation can be viewed. Barnard (1978) described a typical bucket dredge operating in an estuary as producing a downstream turbidity plume about 300 m long at the surface and 500 m long at the bottom. Field studies indicate that downcurrent suspended solids concentrations may vary from approximately 150 to 900 mg/ℓ within 30.5 m of the dredge, from 100 to 600 mg/ℓ within 61 m of the dredge, and from 75 to 350 mg/ℓ within 274 m of the dredge (Hayes 1986). Resuspension of sediments during bucket dredging operations is primarily a near-field phenomenon and thus represents a small temporal- and spatial-scale perturbation of the suspended sediment field (Bohlen and Tramontano 1977; Barnard 1978; Bohlen, Cundy, and Tramontano 1979; Lunz, Clarke, and Fredette 1984). Suspended sediment concentrations observed during clamshell dredging and barge overflow operations at MOTSU (see Part IV) were well within these limits.

95. It is the suspension of sediments in the water column during dredging operations that is most often the source of environmental concern (Lunz and LaSalle 1986, Barr 1987). The environmental effects of sediment suspension can be broadly grouped into two categories: water quality alterations and direct effects on organisms by the sediments (National Research Council 1985, Barr 1987). Water quality concerns center on reductions in dissolved oxygen (DO) concentrations or on the release of sediment contaminants (National Research Council 1985; Barr 1987; LaSalle et al., in preparation). Other

water quality concerns, including the release of naturally occurring sediment compounds (e.g. sulfates and nutrients, see Tavolaro and Mansky 1984 for a discussion) and changes in pH, light transmission, temperature, and other water variables (see LaSalle et al., in preparation), while of potential significance in certain cases, are generally unimportant (McCauley, Parr, and Hancock 1977; National Research Council 1985; Barr 1987).

96. Suspended sediments, in high concentrations, can directly affect the health and survival of aquatic organisms. Lethal and sublethal effects on all life stages of aquatic organisms have been reported, including burial, clogging of respiratory organs, membrane abrasion, impairment of feeding and other activities, and deleterious effects on survival and growth of critical egg and larval stages (see reviews in Sherk, O'Connor, and Neumann 1975; Peddicord and McFarland 1978; Stern and Stickle 1978; National Research Council 1985; Barr 1987, LaSalle et al., in preparation). Effects on behavior (mating, feeding, migration) and synergistic effects of two or more factors have been suggested to be important but are not established (LaSalle et al., in preparation; Manooch, in preparation; cf. Gibson 1987).

97. Information on the effects of suspended sediments on aquatic organisms is incomplete, widely scattered, occasionally contradictory, and suffers from a lack of standardization in experimental protocol (Lunz, Clarke, and Fredette 1984; Barr 1987; LaSalle et al., in preparation). In general, technical evidence supporting environmental concerns about suspended sediment effects is not strong. On the contrary, even when the shortcomings and inconsistencies of the evidence are recognized, the available data suggest that the life stages of most and probably all species adapted to naturally turbid estuarine conditions are moderately to extremely tolerant of elevated suspended sediment concentrations (Lunz, Clarke, and Fredette 1984; Carricker 1986; Barr 1987).

98. In view of the limited technical data base, it is important that information gathered from the literature on environmental effects of suspended sediments be viewed in the context of the natural range of conditions at a site and that the temporal and spatial scales of project-related environmental effects be considered in that context (Barr 1987; LaSalle et al., in preparation).

Environmental Characteristics of the Study Site

Description

99. The ranges and maxima of important environmental characteristics of the Cape Fear River at MOTSU are as follows:

a. Riverflows may vary from a few hundred cubic feet per second to over 200,000 cfs (5,660 cm/sec) over a tidal cycle at the mouth of Cape Fear River (US Army Engineer District (USAED), Wilmington 1984); mean riverflows range from about 90 to 135 cm/sec in the main channel near MOTSU (USAED, Wilmington 1960).

b. Suspended sediment concentrations range over the year from 10 to 250 mg/ℓ at the surface to 30 to 900 mg/ℓ near the bottom (USAED, Wilmington 1984).

c. Sediment deposition at MOTSU has frequently averaged 1 in. per week, and over 6 ft has been deposited in a 2-week period during spring floods.*

d. The mean tide range at Wilmington is about 3.4 ft, with a maximum flood tide of 8.3 ft and a maximum wind tide of about 10.6 ft (USAED, Wilmington 1960).

100. A number of mechanisms act to put sediments into suspension (see Postma 1967). While the suspended sediment levels associated with these events are not well documented for the Cape Fear River, values recorded at other estuarine locations may be applicable. Winds associated with storms may commonly raise suspended sediment levels in estuaries and embayments to 1,000 to 1,500 mg/ℓ (Oviatt et al. 1981, Sosnowski 1984, Gabrielson and Lukatelich 1975, Stumpf 1988). Seasonal and storm-associated river flooding and runoff often elevate suspended sediment levels by 100 to 150 mg/ℓ, and peaks of over 600 mg/ℓ have been recorded in Southeastern estuaries (Biggs 1970, Bohlen 1975, Stumpf 1988). Tides and other estuarine circulation (Oviatt and Nixon 1975, Demers et al. 1987) may raise suspended sediment levels at least 50 mg/ℓ, and suspended sediment levels over 1,000 mg/ℓ have been reported during spring tides (Vale and Sundby 1987). Shrimp trawls (May 1973; Markay and Putman 1976; Schubel, Carter, and Wise 1979) may resuspend sediments and increase the suspended sediment concentration to 5,000 mg/ℓ at the trawl to 100 to 500 mg/ℓ at a point 100 m astern (Schubel, Williams, and Wise 1977).

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* Military Traffic Management Command. 1984. "Deficiencies in and Achievement of Required Level of Preparedness, Harbor Facilities: Military Ocean Terminal, Sunny Point, North Carolina," Washington, DC.

Effects of ship traffic (primarily resuspension from pressure waves and propeller wash) have not been accurately measured, but may be important sources of suspended sediment in estuarine areas subject to navigation traffic (McCauley, Parr, and Hancock 1977). Based on studies in freshwater environments, several hundred to over 1,000 mg/ℓ of sediment may be resuspended in ship passage (Holland 1986; Aldridge, Payne, and Miller 1987).

Observed changes due to dredging and overflow

101. Environmental effects of clamshell dredging and barge overflow at MOTSU were very localized and short lived. Current speeds ranged from 16 to 60 cm/sec on the four sampling dates, effectively dispersing the downcurrent turbidity plume, mixing in oxygenated water, and equilibrating water temperature. Background DO levels ranged from 5.2 mg/ℓ (bottom) to 5.7 mg/ℓ (surface). Reductions in DO ranged from undetectable to a maximum of 13 percent in one case, but most DO reductions were insignificant at 5 percent of ambient or less. No differences were noted among plume and ambient water temperatures.

102. Background turbidity levels (suspended sediment concentrations for each turbidity reading, calculated from reference samples, are given in parentheses) varied significantly over the sampling dates. Ambient water column turbidity (flood and ebb values) averaged 7.1 to 8.5 NTU (39.3 to 44.2 mg/ℓ) on September 24 (range 4.0 NTU (28.8 mg/ℓ) at the surface to 10.4 NTU (51.0 mg/ℓ) near the bottom). On September 30, water column turbidity averaged 7.8 NTU (28.6 mg/ℓ) and ranged from 4.3 NTU (20.5 mg/ℓ) at the surface to 13 NTU (42.5 mg/ℓ) near the bottom. Ebb and flood turbidity on October 20 averaged 7.5 to 12.7 NTU (31.1 to 50.4 mg/ℓ) and ranged from 6.3 NTU (26.9 mg/ℓ) at the surface to 17.0 NTU (67.6 mg/ℓ) near bottom. The October 21 background data are incomplete and are not included in this discussion.

103. Maximum turbidities were observed at the dredging site on October 21 during overflow; values of 72 NTU (327 mg/ℓ) at the surface and 150 NTU (739 mg/ℓ) near the bottom were recorded at the barge. However, these suspended sediment levels were extremely short-lived and localized. Downstream samples taken during dredging and dredging plus overflow could not distinguish among the overflow and dredging turbidity plumes at any distance.

104. Dredging increased water column turbidity in the vicinity of the dredging operation. Levels of suspended sediment in surface and midwater

samples generally decreased rapidly with increasing distance from the operation. Maximum turbidity levels observed at a distance of 30 m downcurrent of the dredging site on any sampling date were 55 NTU (203 mg/ℓ) on October 21 for surface samples and 54 NTU (214 mg/ℓ) on October 20 for bottom waters. Given as increases above background levels, the maxima at 30 m downcurrent were 28 NTU (87 mg/ℓ) and 37 NTU (162 mg/ℓ), respectively. Increases in turbidity above background in most cases were much less, as illustrated by the following data collected on September 24 and 30.

105. During dredging operations on September 24, mean increases in surface turbidity were 8.8, 2.8, and 4.8 NTU (45.2, 24.9 and 31.4 mg/ℓ) above ambient at 30, 150, and 300 m downcurrent on flood tide. Mean surface turbidity increases on the ebb ranged from 14.2 NTU (65.4 mg/ℓ) above background at 30 m downcurrent to 1.7 NTU (21.4 mg/ℓ) above background at 300 m. At 30, 150, and 300 m, bottom turbidity increased 12.1, 0, and 8.1 NTU (57.4, 0, and 42.8 mg/ℓ) above ambient on the flood and ranged from 14.1 NTU (65.1 mg/ℓ) above background at 30 m downcurrent to no difference at 300 m on the ebb.

106. On September 30, mean increases in surface turbidity were 2.0, 0.3, and 1.0 NTU (15.7, 12.5, and 13.8 mg/ℓ) above background at 30, 150, and 300 m downcurrent. Bottom turbidity was 5.2, 8.8, and 10.8 NTU (22.5, 31.1, and 36.4 mg/ℓ) above background at the same distances downcurrent.

107. Most of the sediments released at the dredging site during dredging or overflow settled out of suspension in less than 30 m. Increases in suspended sediment concentrations over daily background levels were not large when viewed against the historical range and variability of background levels on a daily and monthly basis. Indeed, the increases are minor when compared with seasonal or historical levels (USAED, Wilmington 1984; see also Military Traffic Management Command 1984, op. cit.) or with suspended sediment levels expected from ship traffic (e.g., Aldridge, Payne, and Miller 1987), trawl fishing (e.g., Schubel, Carter, and Wise 1979), or events such as wind, storms, and runoff (e.g., Bohlen 1975, Stumpf 1988).

Biological Response of Benthos

108. The sediment released during dredging or barge overflow is not expected to have a major or long-term detrimental effect on the benthic community at the site. There are a number of reasons for this conclusion. First,

the amount of sediment released during this operation was relatively small. Tidal and river currents at the site rapidly dispersed and diluted the released sediments. Second, had any sediment deposition occurred, the small amounts involved and the demonstrated ability of many estuarine organisms to burrow through overburden up to several inches thick (e.g., Maurer 1967; McCauley, Hancock, and Parr 1976, Brenchley 1981; Tur.. and Risk 1981; Maurer et al. 1986) would have minimized the effect of sedimentation. Third, because the dredging occurred at a time when a strong seasonal benthic recruitment pulse occurs in North Carolina estuaries, defaunated areas, should any have been created, would have been rapidly (on the order of weeks) recolonized (Commito 1976, Homziak 1985). Fourth, the volume of ship traffic in the terminal area and the frequency and intensity of sediment deposition at the site suggest that the benthic community in the area is frequently perturbed by both scour and sedimentation. Thus, any sedimentation effects on the benthos in the project area must be viewed in that context.

Biological Response of Fishes

109. The major environmental alterations associated with bucket dredging and barge overflow are elevated suspended sediment levels, sedimentation, reduced DO levels, and channel blockage. As discussed below, a review of the literature suggests that no adverse effects to fishes should be expected in the vicinity of the MOTSU dredging project.

Suspended sediments

110. Eggs and larvae. Resource agencies are particularly concerned about the potential detrimental effects of dredging-associated environmental alterations, particularly suspended sediment effects, on the eggs and larvae of marine and estuarine fishes. These life stages are particularly sensitive to stress (Rosenthal and Alderdice 1976), and it is the success of the egg and larval stages that ultimately determines the survival and strength of a given year class of fishes. However, because the causal factors by which suspended sediments affect eggs and larval fishes are complex and poorly understood, it is difficult to draw clear conclusions from published studies on effects of suspended sediment on fish eggs and larvae. Because field studies have not produced accurate quantitative mortality estimates, most information is derived from laboratory studies. Good reviews of studies evaluating suspended

sediment effects on fish eggs and larvae are provided by Schubel, Williams, and Wise (1977) and Priest (1981). In addition, a series of studies in the upper Chesapeake Bay system, particularly in connection with striped bass spawning grounds in the vicinity of the Chesapeake and Delaware Canal (Schubel and Wang 1973; Auld and Schubel 1978; Morgan, Rasin, and Noe 1983), apply directly to assessing fisheries impacts at the MOTSU dredging site. Table 8 (taken from LaSalle et al., in preparation), although not a comprehensive compilation, provides a sample of the results of relevant investigations.

111. The majority of investigations have shown that, at experimental suspended sediment concentrations similar to those observed during bucket dredging and barge overflow, detrimental effects on eggs and larvae of fishes are not apparent. For example, Schubel, Williams, and Wise (1977) concluded that semibuoyant striped bass (*Morone saxitalis*) eggs can tolerate very high suspended sediment levels (≥1,000 mg/ℓ) for periods of many hours. Similarly, Kiorboe et al. (1981) reported that embryonic development and hatching of herring (*Clupea harengus*) were unaffected by either long-term exposure (10 days) to low to moderate concentrations (5 to 300 mg/ℓ) of suspended silt or short-term exposure (2 hr) to higher concentrations (500 mg/ℓ) of silt.

112. There is some indication that larval stages may be more sensitive to elevated suspended sediment concentrations than are eggs of the same species (Auld and Schubel 1978). Boehlert (1984) also found that adhesion of sediment particles to the epidermis may exert a smothering effect, although adhesion was noted only at concentrations above 1,000 mg/ℓ, which is well above that found in this or other dredging operations. Boehlert (1984) also observed severe abrasion damage in larvae of Pacific herring (*Clupea harengus pallasi*) only at concentrations at or above 4,000 mg/ℓ (larvae exposed to experimental concentrations for 24 hr). Although larvae did not show significant mortality at any experimental concentration (up to 8,000 mg/ℓ), observed effects could represent sublethal stress that may contribute to later mortality. Priest (1981) concluded that suspended sediment concentrations sufficient to produce a 50-percent mortality in laboratory experiments of larvae of the studied fish species were far in excess of levels characteristic of dredging operations.

113. In summary, based on reviews of studies conducted to date (Table 8), eggs and larvae of estuarine-dependent species appear to be very tolerant of elevated suspended sediment concentrations. In all probability, eggs and larvae of fishes that use naturally turbid estuarine habitats as spawning and

Table 8

Results of Experimental Determinations of Effects of Suspended Sediments on Various Life History Stages of Fishes (Modified from Priest 1981)

Species	Stage	Suspended Sediment Concentration, mg/ℓ	Exposure Duration	Type of Sediment	Degree of Effect	Reference
Yellow perch	Eggs	500	Not stated	Natural	No significant effect on hatching success; some delay in time to hatching noted in samples at ~100 mg/ℓ (for all species)	Schubel and Wang (1973)
White perch						
Striped bass						
Alewife						
White perch		50-5,250		Natural (fine)	No significant effect on hatching success; definite delay in development at ≥1,500 mg/ℓ	Morgan, Rasin, and Noe (1983)
		20-2,300		Natural (fine)		
Striped bass					No significant effect on hatching success; definite delay in development at ≥1,300 mg/ℓ	
Atlantic herring		5-300	10 days	Natural	No significant effect on development or hatching success	Kiorboe et al. (1981)
		500	2 hr	Natural		
Blueback herring		50-5,000	Not stated	Natural (fine)	No significant effect on hatching success at all test concentrations	Auld and Schubel (1978)
Alewife					(Same as above)	
American shad					(Same as above)	
Yellow perch					(Same as above)	
White perch					Significant effect on hatching success at 1,000 mg/ℓ, but not at lower concentrations	Morgan, Rasin, and Noe (1983)
Striped bass					(Same as above)	Auld and Schubel (1978)
White perch	Larvae	1,626-5,380	24-48 hr		15-49 percent mortality	
Striped bass		1,557-5,210	24-48 hr		20-57 percent mortality	
Yellow perch		50-1,000	4 days	Natural	Survival significantly reduced at ≥500 mg/ℓ	
Striped bass		50-1,000	2-3 days	Natural	(Same as above)	
Alewife		50-1,000	4 days	Natural	Survival significantly reduced at ≥100 mg/ℓ	
Spot	Adult	13,090	24 hr	Artificial	LC_{10}	Sherk, O'Connor, and Neumann (1975)
Spot		68,750		Natural		
Striped killifish		23,770		Artificial		
Striped killifish		97,200		Natural		
Mummichog		24,470		Artificial		
Atlantic silverside		580		Artificial		
Bay anchovy		2,300		Artificial		
White perch		9,970		Natural		
White perch		3,050		Artificial		
Striped bass	Subadult	4,000	21 days	Natural	LC_{10}	Peddicord and McFarland (1978)
Cunner	Adult	133,000	12 hr	Natural (silt)	Median tolerance limit	Rogers (1969)
Cunner		100,000	24 hr		Median tolerance limit	
Cunner		72,000	48 hr		Median tolerance limit	
Mummichog		300,000	24 hr		No mortality	
Sheepshead minnow		300,000	24 hr		<30 percent mortality	
Cunner		100,000	24 hr		Median tolerance limit	
Stickleback		52,000	24 hr		Median tolerance limit	

nursery grounds are adapted to and highly tolerant of elevated suspended sediment concentrations. A very conservative level at which no adverse effects would be expected would be 500 mg/ℓ (LaSalle et al., in preparation). Indeed, a strong case can be made for a 1,000-mg/ℓ limit within 500 m of a dredge as posing little or no risk to eggs and larvae of fishes. Such conditions did not prevail at the dredge site or for barge overflow for sufficient lengths of time to merit special concern.

114. Juvenile stages. The literature is sparse and incomplete on the direct physical effects of elevated suspended sediment concentrations on juvenile stages. Wallen (1951) exposed both adults and juveniles of a number of freshwater fish species to a wide range of silt-clay suspensions, well above concentrations found under typical dredging conditions. While results for juveniles were not presented separately, Wallen (1951) concluded that suspended silt-clay at those concentrations was not lethal and did not produce observable symptoms in juvenile fishes. Sherk, O'Connor, and Neumann (1975), working with juvenile Atlantic menhaden (*Brevoortia tyrannus*), determined that a lethal concentration producing 10-percent mortality (LC_{10} value) of 1,540 mg/ℓ was obtained after a 24-hr exposure to Fuller's earth (a combination of clay and siliceous material). Using in situ bioassays, Jeane and Pine (1975) studied the effects of elevated turbidities at dredging sites on juvenile chinook salmon. No significant mortality was observed among juveniles exposed to fine sediment suspensions. Based on the little information available, there is no indication that dredging operations pose unacceptable risks to juvenile fishes, especially if project-specific variables limit the spatial and temporal extent of the affected areas, as was the case in this operation.

115. Adult stages. A considerable body of relevant literature on the direct physical effects of elevated suspended sediment concentrations on adult fishes exists. While interpretation of this literature is limited by the lack of standardization among experiments and differing experimental protocols, it is evident that lethal and sublethal effects of elevated suspended sediment concentrations on adult fishes do not occur until levels far in excess of those observed in this and other dredging and barge overflow operations are reached.

116. Wallen (1951) found lethal turbidity thresholds to be equal to or greater than 16,500 mg/ℓ following exposure durations from 3.5 to 17 days in

16 species of freshwater fishes. Behavioral signs of stress for most species were not apparent at suspended sediment concentrations under 20,000 mg/ℓ. Peddicord and McFarland (1978) determined that rainbow trout, a fish of highly oxygenated and clear waters, showed no significant mortality after 22 days at concentrations at or below 2,000 mg/ℓ, and 95-percent survival occurred at concentrations approaching 4,300 mg/ℓ. Other studies have exposed caged specimens to in situ levels of suspended and deposited sediments at actual dredging sites (Ingle 1952, Ritchie 1970) with few or no detrimental effects. Ritchie (1970) found no evidence of gill pathology in specimens of 11 estuarine fish species prior to and after exposure to dredging conditions. Sherk, O'Connor, and Neumann (1975), however, found disrupted gill tissue and increased mucus production in white perch exposed to sublethal suspended sediment concentrations (650 mg/ℓ).

117. A great deal of evidence supports the fact that adult and juvenile stages of estuarine fishes are moderately to extremely tolerant of elevated suspended sediment concentrations. Because the levels of suspended sediment surrounding the bucket dredging activity and barge overflow were far below 1,000 mg/ℓ and the elevated levels of suspended sediment were confined to a relatively small area immediately surrounding the dredging site, there appears to be no justification to predict significant dredging-induced physical effects on juvenile and adult estuarine fishes. Because fishes are highly mobile organisms and the duration of elevated levels of suspended sediments was short, there is no justification to suspect that adult fishes would be subjected to elevated suspended sediment levels for sufficient periods of time to incur even sublethal adverse effects.

Sedimentation

118. A number of fish species deposit demersal (often adhesive) eggs that generally remain in place on the bottom until larval hatching. There is a concern that heightened sedimentation rates in project areas may lead to smothering of these eggs. Because of the dispersive effects of currents on suspended sediments at the site and the lack of spawning activity, no effect of sedimentation on eggs or larvae of fishes is expected. Juveniles and adults of practically all fishes are sufficiently mobile to avoid burial due to increased sedimentation rates or prolonged exposures to suspended sediments at a dredging site. While the major impact on these stages is the potential

loss of benthic food resources, the limited impact on benthic communities effectively removes this as a cause for concern.

Dissolved oxygen

119. The reduction of DO (to levels below 1 to 2 ppm) is primarily of concern to demersal eggs of fishes in the vicinity of a dredging or disposal operation. Dissolved oxygen reduction is a short-term phenomenon, on the order of hours (see Barr 1987; LaSalle et al., in preparation). As with sedimentation, juvenile and adult fishes are capable of avoiding localized areas of low oxygen content. Since DO concentrations were not reduced to critical levels at the dredging site because of the rapid mixing and water exchange, little concern is warranted for the effects of reduced dissolved oxygen.

Channel blockage

120. The presence of the dredging equipment or the suspended sediment plume itself has been suggested to have an effect on the distribution and movement of juvenile and adult fishes, particularly anadromous fishes. There is little evidence, however, to support the contention that elevated suspended sediment levels significantly affect fish migration. The only available information that treats the subject in even a cursory manner is a few observations of the attraction of fishes to dredging operations (Ingle 1952, Maragos et al. 1977) and a study by Harper (1973), who reported on trawl samples taken in a sediment disposal plume versus "clear" ambient water. Harper (1973) found that where abundances of individuals differed between turbid and ambient water samples, the average number of individuals in turbid plume waters was much larger. Additional comparisons of fish abundances in naturally turbid versus clear water again showed that, where differences occurred, the average number of individuals and the fish biomass were higher in the turbid water.

121. More recent work (Cyrus and Blaber 1987a,b) suggests that juveniles of fishes inhabiting estuaries either prefer turbid water of varying degrees or appear to be indifferent to turbidity. These results suggest that suspended sediment levels probably had no effect on fall migration downstream of juvenile shad, alewives, blueback herring, and striped bass. As discussed previously, juveniles of these species are known to tolerate the suspended sediment concentrations equal to those present in the project area. In addition, elevated suspended sediment levels were restricted to a relatively small area of the passable river (the Cape Fear River is over 2 miles wide at MOTSU)

(USAED, Wilmington 1960) and, because the suspended material rapidly settled or dispersed, the frequent interruption of dredging operations allowed for numerous periods when no dredging-associated suspended sediment was present.

Biological Response of Shellfish

Suspended sediment

122. Most shellfishes inhabiting turbid estuaries have been shown to be tolerant of suspended sediment concentrations significantly greater (several thousand milligrams per litre and above) than the levels observed in this study. A review of the published literature (Table 9) reveals that most reported detrimental effects on shellfish were for suspended sediment levels many times higher than those reported for dredging operations and for exposure periods of 5 days to over 3 weeks (Stern and Stickle 1978; Priest 1981; LaSalle et al., in preparation). Because average suspended sediment levels were generally elevated by only tens of milligrams per litre during dredging and overflow operations and periods of increased suspended sediment concentrations were limited to, at most, several hours at a time, there is no reason to expect that shellfish resources would be detrimentally affected by the dredging or overflow operations. Indeed, the suspended sediment concentrations observed during dredging and overflow did not exceed levels to which local shellfish resources are regularly exposed in the Cape Fear River estuary (USAED, Wilmington 1960, 1984; see also Military Traffic Management Command 1984, op. cit.).

123. While significant recreational or commercial oyster resources have not been reported in the vicinity of the dredging site, it is useful to review the known suspended sediment effects on this important species. Reduced respiratory pumping rates observed by Loosanoff and Tommers (1948) for oysters held at suspended sediment concentrations between 100 and 4,000 mg/ℓ are an example of a compensatory mechanism that enables these sessile bivalves to effectively limit their exposure to adverse environmental conditions over at least short-term durations. Exposure to these concentrations for even extended periods had no adverse effect on adult oysters. Davis and Hidu (1969) reported substantial (22 percent) incidences of abnormal development in American oyster eggs exposed to suspended sediment concentrations within the range occasionally encountered in the immediate vicinity of the bucket

Table 9

Results of Experimental Determinations of Effects of Suspended Sediments on Various Life History Stages of Shellfishes

Species	Stage	Suspended Sediment Concentration, mg/ℓ	Exposure Duration	Type of Sediment	Degree of Effect	Reference
American oyster	Eggs	188	Not stated	Natural (silt)	22 percent abnormal development	Davis and Hidu (1969)
		250		Natural (silt)	27 percent abnormal development	
		375		Natural (silt)	34 percent abnormal development	
		1,000		Artificial	No significant effect	
		2,000		Artificial	No significant effect	
	Larvae	750	12 days	Natural (silt)	31 percent mortality	
	Larvae	2,000	12 days	Artificial	20 percent mortality	
	Larvae	500	Not stated	Artificial	78 percent mortality	
Hard clam	Eggs	750		Natural (silt)	8 percent abnormal development	Davis (1960)
		1,000		Natural (silt)	21 percent abnormal development	
		1,500		Natural (silt)	35 percent abnormal development	
		125		Artificial	18 percent abnormal development	
		125		Artificial	25 percent abnormal development	
		4,000		Artificial	31 percent abnormal development	Davis and Hidu (1969)
	Larvae	1,000		Natural (silt)	No significant effect	Davis (1960)
	Larvae	500	12 days	Artificial	50 percent mortality	
Spot-tailed sand shrimp	Adult	50,000	200 hr	Artificial	LC_{50}	Peddicord et al. (1975)
Black-tailed sand shrimp	Subadult	21,500	21 days	Natural (contaminated)	20 percent mortality	Peddicord and McFarland (1978)
Dungeness crab	Adult	3,500	21 days	Natural (contaminated)	LC_{10}	
Dungeness crab	Juvenile	2,000-20,000	25 days	Natural	No mortality at <4,300 mg/ℓ; 38-percent mortality at 9,200 mg/ℓ; abnormalities between 1,800 and 4,300 mg/ℓ	Peddicord and McFarland (1978)
American oyster	Adult	4,000-32,000	Extended	Not stated	Detrimental	Wilson (1950)
American oyster	Adult	100-700	Not stated	Mud	No effect	Mackin (1961)
American oyster	Adult	100-4,000	Not stated	Silt	Reduced pumping	Loosanoff and Tommers (1948)
Blue mussel	Subadult	100,000	5 days	Artificial	10 percent mortality	Peddicord et al. (1975)
Blue mussel	Adult	100,000	11 days	Artificial	10 percent mortality	
Blue mussel	Adult	96,000	200 hr	Artificial	LC_{50}	

Sources: Priest 1981; LaSalle et al., in preparation.

dredging and barge overflow operations, although exposure durations were not stated. In contrast, developing oyster larvae showed enhanced growth rates at suspended sediment concentrations up to 500 mg/ℓ (Davis 1960, Davis and Hidu 1969). Higher concentrations did hinder growth and result in increased mortality.

124. Carricker (1986) provides an excellent review of the literature dealing with suspended sediment effects on oyster larvae. In general, concentrations below about 180 mg/ℓ for embryos and below 500 mg/ℓ for veligers can be beneficial, while higher concentrations appear to become increasingly harmful. Suspended sediment apparently has little effect on feeding or movement of larvae through the water column.

Sedimentation

125. Juveniles of shellfishes that assume sessile (e.g., oyster spat) or burrowing (e.g., clams) modes of existence may be particularly vulnerable to increased sedimentation rates in the vicinity of dredging operations. An additional concern involves the possible hindrance of settling by oyster larvae on hard surfaces covered by silt. Galtsoff (1964) suggested that as little as 1 to 2 mm of silt may be sufficient to prevent settling on shell cultch. As pointed out by Carricker (1986), however, the fact that larvae can attach to surfaces fouled by mucoid films, microbes, and detritus suggests that oyster larvae are indeed capable of dealing with relatively unclean surfaces. Sedimentation rates induced by this dredging and overflow operation were small and the mixing and dispersive effects of tidal and river currents great, suggesting that project-generated sedimentation is an inconsequential concern for adult and juvenile shellfish.

Dissolved oxygen

126. The reduction of DO to levels below 1 to 2 ppm may potentially affect demersal eggs, larvae, or adults of shellfishes in the vicinity of a dredging or disposal operation. However, DO levels in the sediment plume were not depressed to critical levels for any shellfish life stage. For example, Morrison (1971) reported that the eggs of the hard clam, *Mercenaria*, were tolerant of oxygen concentrations as low as 0.5 ppm, with death occurring only at 0.2 ppm. Eggs or larvae of oysters are not known to be adversely affected by DO levels similar to those observed at the project site (see review in Sellers and Stanley 1984). A review by Bishop, Gosselink, and Stone (1980) suggests that shrimp would be unaffected by even the lowest DO levels recorded

at the project site. In any event, nonsessile juvenile and adult shellfishes are capable of avoiding areas of low oxygen content, while sessile or limited mobility forms (e.g., bivalves) can isolate themselves from unfavorable water conditions for extended periods. The degree to which DO was reduced in the area of dredging and barge overflow operations, however, was not significant, and the duration of any effect was extremely short.

Channel blockage

127. The suspended sediment plume generated by the dredge and the overflow has been suggested to affect the distribution and movement of juvenile and adult shellfishes such as crabs and shrimp. While suspended sediment effects on blue crabs are not well known, Van Engel (1982) notes that there appears to be a decrease in soft-shell crab landings following storm events that increase suspended sediment levels. However, he also points out that such storms also decrease salinity, increase concentrations of pollutants, and introduce other confounding factors, so it is not possible to evaluate the potential impact of increased suspended sediments alone on blue crab populations from these observations. Because increases in suspended sediment concentrations at the project site were limited in time and space, and because blue crabs are normally found in areas subject to suspended sediment levels equal to or greater than those observed in this study (e.g., the Chesapeake Bay; Stumpf 1988), no effect on blue crab populations is expected.

128. Harper (1973) reported that the average number of macrobenthic invertebrates in the turbid waters of a sediment disposal was much greater than in ambient water in winter. Where differences in abundances occurred, the blue crab, brown shrimp (*Penaeus aztecus*), and grass shrimp (*Palaemontes pugio*) were more abundant in turbid rather than ambient water. White shrimp, *Penaeus setiferus*, did not differ in abundance between ambient and turbid water samples.

129. Other observations and experimental evidence support the preference of brown shrimp for turbid waters. Viosca (1958) and May (1973) reported brown shrimp to be attracted to the turbid water around operating dredges. Brown shrimp are also generally found on bottoms of easily suspended fine silts and clays, and actively selected such fine substrate bottoms in laboratory studies (see review in Larsen, Van Den Avyle, and Bozeman 1986). Both brown and white shrimp are closely associated with waters containing high levels of suspended sediment (e.g., Kutkuhn 1966), illustrated by studies that

have shown inshore shrimp catches along the gulf coast to be positively correlated with estuarine turbidity (Linder and Baily 1969). Both brown and and white shrimp have been shown to increase activity and to more effectively avoid predation in turbid water (Minello, Zimmerman, and Martinez 1986). Both brown and white shrimp appear to prefer low-light, turbid-water conditions (see reviews in Muncy 1984 and Larsen, Van Den Avyle, and Bozeman 1986). Indeed, shrimping itself often generates suspended sediment levels far in excess of those observed in this or any other dredging operation (Markay and Putnam 1976; Schubel, Carter, and Wise 1979) with no apparent detrimental suspended sediment effects on the target shrimp populations.

130. As with other fish and shellfish species discussed, the relatively low levels of suspended sediment generated by the project, as well as the limited area potentially affected and the short duration of increased suspended sediment levels, suggest that shrimp and blue crab populations, had they been present, would not have been adversely affected. Movement of white shrimp, known to migrate downstream at about the time when the dredging occurred (Muncy 1984), should also have been unaffected.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

131. Based on the results of field sampling and monitoring, the following conclusions regarding the barge loading and overflow characteristics are made:

- a. The sediment dredged during this study was predominantly a highly plastic clay (CH), with traces of sand. The use of an 18-cu yd clamshell dredge for removal of the material resulted in some spillage and leakage of dredged material and water during the dredging process.
- b. The material placed in the barge was observed to be composed of a combination of entrapped water, fluid slurrylike material, and stiffer clumps of sediment. Considerable variation in the nature of material in respective bucket loads was observed. As the barges were filled, the more fluid material was displaced to the surface and comprised the overflow.
- c. The load gained during the period of overflow in three tests varied from 1.4 to 3.2 percent, with corresponding times of overflow from 9 to 28 min. These overflow times were based on the dredge operator's perception of economic load. The load gained by filling the disposal barge in one test from a level 1 ft below the coaming to the point of overflow was approximately 6.9 percent. This, added to the load gained during overflow, corresponded to a total increase in load of 10.1 percent for this test.
- d. The suspended solids concentration of the overflow increased with time of overflow. The average concentration at the start of overflow was 88 g/ℓ as compared with 248 g/ℓ at the end of overflow.
- e. Grain size distribution of material in the barges increased with depth, and average grain size of overflow solids was finer than in situ sediment. This indicates that a sorting process occurs in the barges during the loading of even predominantly fine-grained materials. This could be due either to settling of sand particles or to an initially finer distribution of the more fluid fractions of the material which comprise the overflow.

132. Based on the field data and laboratory tests conducted for this study, the following conclusions regarding the suspended sediment plumes are made:

- a. Background water column suspended solids concentration during the study ranged from 10 to 40 mg/ℓ.
- b. Plumes from clamshell bucket spillage were observed to be patchy in nature, were advected downcurrent, and mixed with the ambient water downstream. Due to the short duration of overflow, sampling of the overflow plumes was difficult.

c. The average suspended solids concentration of samples in the plumes generated by dredging was 47 mg/ℓ above background, while that for plumes generated by dredging with overflow was 65 mg/ℓ above background. No statistically significant difference was found between the total suspended solids of plumes resulting from dredging and those resulting from dredging with overflow.

d. No general relationship was found between suspended solids concentrations and distance downstream. The suspended solids concentrations in the plumes were reduced to near-background levels at short distances from the dredging activity.

e. An analytical model of the suspended sediment concentrations indicated that the material settles rapidly without being transported, and only a small fraction of the suspended material would go into far-field suspension.

133. Based on a review of literature, the following conclusions concerning the biological effects of dredging and overflow are made:

a. Technical information currently available is insufficient to accurately predict the degree of risk which given concentrations of suspended sediments of known characteristics pose to egg, larval, or juvenile stages of most fish and shellfish resources. However, qualitative predictions are possible.

b. Based on a thorough review of studies conducted to date, eggs and larvae of estuarine-dependent fish and shellfish species appear to be very tolerant to elevated suspended sediment concentrations. Evidence suggests that eggs and larvae of fishes and shellfishes that utilize naturally turbid habitats as spawning and nursery grounds, or pass through such areas as migrating juveniles, are adapted to and highly tolerant of elevated suspended sediment concentrations.

c. Similarly, adults and juveniles that inhabit turbid estuaries and coastal waters are adapted to and tolerant of elevated suspended sediment concentrations for reasonable lengths of time. There is, therefore, little reason to suspect that the various life stages of these species cannot tolerate the suspended sediment levels typical of most dredging operations.

d. When viewed against data on naturally occurring minimum, average, and maximum suspended sediment concentrations (and their temporal and spatial scales) at the MOTSU project site, the suspended sediment levels observed during clamshell dredging and barge overflow most probably did not produce any significant adverse environmental effect.

Recommendations

134. Based on the results of this study, the following recommendations are made:

a. If clamshell equipment is again used for maintenance dredging, additional studies of barge loading characteristics should be conducted. These additional studies should be limited to determination of the additional load gained by longer periods of overflow.

b. Monitoring of additional barge loading studies should include plume definition for the longer periods of overflow and measurements of the accumulated thickness of deposited sediment as a function of distance from the overflow.

c. Current constraints on overflow are not technically warranted; therefore, discussions should be initiated with concerned resource agencies to lift the overflow restrictions.

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